A STUDY OF EFFECT OF WEIGHT AND DIRECTION ON THE SPEED, ACCURACY, AND PHYSIOLOGICAL COST OF ONE HAND MOTIONS IN THE HORIZONTAL PLANE

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INTRODUCTION

Job evaluation is supposed to evaluate the complexity or "worth" of work to help establish criteria for selection, placement and wage payment. Work, however, involves more mental and sensory activities than ever before. Measurements of these mental activities would assist in determining the complexity of work for job design and wage payment evaluation. The present procedures, however, involve judgment of observers to determine the level of qualitative measurements. The people in jobs evaluated by such qualitative techniques question the judgments.

In contrast with many of the techniques developed for analysis of work complexity, the information theory approach provides a basis for evaluation for man's function not only as an operator, but also as part of the man-machine system. The pioneering work to use information theory concepts in the area of industrial engineering is that of Ross (1960). The preliminary experimental work in his paper demonstrates that human work, in certain instances at least, can be broken down into information factors and, when these factors are properly determined, they may be used to provide a measure of work difficulty. However, information techniques could be used for the measurement of purely gross motions, which, while requiring considerable effort, do not require any manipulation or dexterity. This shortcoming of information theory led to the design of this experiment.

Thus, the primary objective of this investigation was to study the effect of physical effort as measured by a force platform on the rate of performance as measured by information theory concepts. This study was restricted to hand movements of the preferred hand in the horizontal plane.

The second objective was to study the effect of various weights and angles using three different criteria:

1. Rate of performance, bits/second.
2. Movement accuracy, percent of hits on target.
3. Physiological cost, measured by a force platform in pound-seconds.

The third objective was to study the effect of weight on the accuracy of inward and outward motions at different angles.

LITERATURE REVIEW

The literature review has been divided into three parts. The first part deals with the basic concepts of information theory and its applications in the areas of industrial engineering. The second part summarizes different investigations which used the output of force platform as the index of physiological cost. The third part is concerned with the experiments carried out for evaluating some of the basic principles of motion economy employed in horizontal arm motions.

1. Information Theory:

Information theory is the discipline growing out of, and now encompassing, a branch of statistical mathematics called the "Mathematics of Communication" or "Communication Theory".

The first practical engineering formulation of Communication Theory began with the work of Shannon (1948) at the Bell Telephone Laboratories although the contemporary work of Wiener (1948) embodies similar concepts. According to Ross, the work of Shannon was preceded by that of Fisher (1925), Szilard (1929), and Hartly (1925).

Because Shannon's work was conceived and developed in the environment of the (electrical) communications engineer, the principle engineering conclusions reached in his work are developed in electrical terms. The term "information" is used in a strict mathematical sense and occurs in the theory in a careful and particular way. It is not synonomous with "meaning". The basic measure of information theory is the "unit of information",

a "bit", which is defined as that which permits a choice between two equally likely events. This definition of information does not permit any measure of the value or intrinsic meaning of what is being transmitted, only its probability of occurence. Information theory does not measure <u>what is</u> transmitted, rather <u>what could have been</u> transmitted.

This relationship is expressed mathematically by the expression:

$$H = - \sum_i p_i \log_2 p_i \text{ bits/symbol} \quad \ldots\ldots\ldots (1)$$

where

H = Average information content per symbol of the communication,

and p_i = Probability of occurence of the ith symbol.

In other words, H is the average expected value of the log of the probability of occurence. Shannon calls this expression the entropy of the information source.

The basic elements of a mechanical communication system are shown in Figure 1. The information source is the device which, in order to produce a desired change in the state of the destination, selects a desired message from a set of possible messages. The transmitter changes (encodes) the message into a signal form which can be conveniently transmitted by the channel. The channel is the device over which the signals representing the message are transmitted to the receiver.

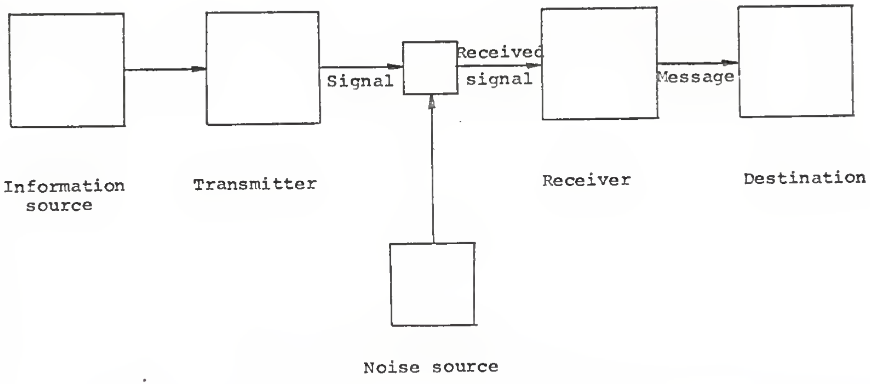


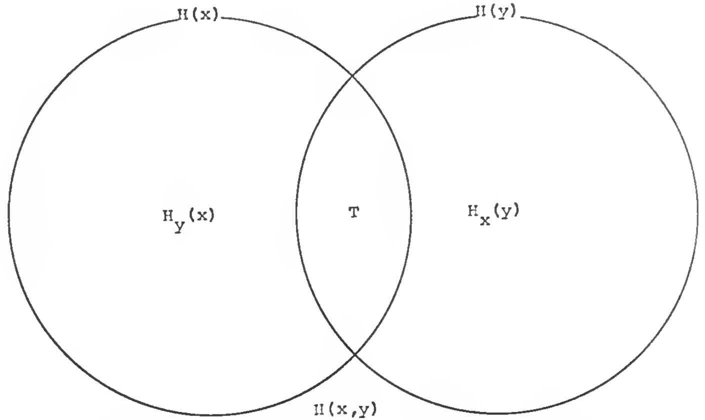
Figure 1. Basic elements of mechanical communication system

The receiver decodes the signal into the message - - normally, in a form meaningful to the receiver.

Noise is said to be any distortions of the original message. Noise (error) may take many forms. However, it is essentially any deviation from the original message. Noise affects the ability to distinguish between alternatives. In general, output is never completely determined by the input because noise interferes with the transmission. Thus the output and input generally are never equal in an information sense.

Garner and Hake (1951) are probably the first to point out that, while the communication engineer normally discusses a system with the relationship of man-machine-man, the psychologist considers the system of machine-man-machine. In this latter scheme, man becomes the communication channel and the information measures are applied by psychologists to his processes. The human operator in a work environment can be considered to be a communication channel; the stimuli presented to him are the inputs and his responses are the outputs. In the psychological applications of information theory, the measure of transmitted information becomes the measure of the organizational functioning of the human and describes the ability to convert complex inputs into complex outputs. The channel capacity becomes the human perception-discrimination-decision-reaction capacity.

In one important paper, Miller (1953) has explained the terminology used in information theory with the help of two partially overlapping circles, Figure 2. The left circle repre-



$H(x)$ = Average amount of input information.

$H(y)$ = Average amount of output information.

$H(x,y)$ = Total information in x and y together

$H_y(x)$ = Information only in x (equivocation).

$H_x(y)$ = Information only in y (noise).

T = Information common to x and y (transmitted information).

Figure 2. Schematic representation of several quantities of information that are involved when messages are received from two related sources (Miller, 1953).

sents the amount of input information, the right represents the amount of output information and the overlap represents the transmitted information. When the amount of input information is increased, the transmitted information will increase at first and will eventually level off at some asymptotic value, the channel capacity of the operator, after which the human operator will begin to make errors. The channel capacity is the upper limit on the extent on which the operator can match his responses to the stimuli given to him.

According to Miller, the channel capacity on the transmitted information can be interpreted as a sort of modern version of the traditional Weber-fraction and is consistent with Theorem 17 in Shannon. Theorem 17 states: the capacity, c, of a channel of band width, W, perturbed by white thermal noise of power, N, when the average transmitter power is P, is given by:

$$c = W \operatorname{Log}_2 \frac{P+N}{N} \qquad \text{.......(2)}$$

(Weber proposed the principle that the ratio between the stimulus and the increment that must be added to it to have a person just notice a difference is invariant with intensity:

$$\frac{\Delta I}{I} = k$$

where I = Stimulus intensity

ΔI = Increment in I

k = Constant.)

Information theory has been used to analyze a number of sensory motor tasks. Crossman (1964) has discussed the information processes in human skill:

> "Skilled performance is a function of sensory, central nervous and motor systems and its ultimate explanation will be physiological. But as yet this has been achieved only for the peripheral elements (sense organs, muscles). We adopt the so-called "black box" approach to the analysis of a complete system (the human "brain and body" system) whose wiring diagram we do not know in detail.
>
> It is clear that the functions in question, such as perception or programming of motor activity, are concerned with storing and processing information, and, to judge from its histology, the brain is well adapted for complex coding operations. So the appropriate conceptional framework for studying the functions would seem to be that of information theory. However, at the input and output ends, where there is direct contact with the environment the ordinary physical laws of energy and motion apply. It goes without saying that we would choose the appropriate "language" for discussing the properties of each separate part of the system."

According to Crossman (1964), the complete system by which sensory information is processed, stored, and used to determine the skilled motor activity can be treated in three stages, concerned respectively with analysis of sensory input data (the receptor system), with the organization of action in relation to current objectives (the central mechanism), and with carrying out the required actions (the effector system).

The human motor behaviour is thought of as a means of generating information. This behaviour can produce in categories of force, direction and time. The information capacity of the motor system is specified by its ability to produce consistently one class of movement from among several alterna-

tive movement classes. The greater the number of alternatives, the greater the information capacity of a particular response.

In serial or self-paced repetitive tasks, such as moving washers from one peg to another, where the subject knows exactly what to do on each trial, the channel capacity is limited by the response itself. Only hand movements so far have been subjected to study and the pioneer work is that of Fitts (1954). He reported several studies of motor performance and made some original suggestions for estimating the information capacity of the human motor system. He shows that, for the human motor system, the amplitude, the direction and the variability of the movements are interrelated.

Considering the motor system as a communication channel, Fitts reasoned that the average amplitude, A, of a human movement is equivalent to the average signal plus noise amplitude. He proposed an index of task difficulty (ID) be defined as

$$ID = Log_2 \frac{A}{N} \qquad ....(3)$$

It can be assumed further, according to Fitts, that

N = W/2 where W is the width of the terminal target.

Hence ID can be evaluated as:

$$ID = Log_2 \frac{A}{W/2} = \frac{A}{.5W}$$

$$= Log_2 \frac{2A}{W} \qquad ....(4)$$

where,

ID = Index of task difficulty, bits.

W = Width of the target within which the movement is required to end, measured parallel to the direction of the movement.

and A = Amplitude of the movement measured from its starting point to the center of target.

On these grounds it was conjectured that average movement time (MT) should remain constant for different values of A and W, within limits, as long as the ID ratio remains constant, that is,

$$\frac{ID}{MT} = c \qquad ....(5)$$

where c may be interpreted as analogous to man's capacity for executing a particular class of motor responses in bits per second. Extending the analogy to the case where ID took on different values, Fitts proposed that

$$MT = a + b\ (ID) \qquad ....(6)$$

where a and b are constants.

He further calculated an index of performance, I_p, from equation (5):

$$I_p = \frac{ID}{MT} = c.$$

He found that the rate of performance in a given type of task is approximately constant over a considerable range of movement amplitudes and tolerance limits but falls off outside this optimum range. As the ID was varied from 2 to 8 bits, the rate of performance was found to lie between 8 and 15 bits/

second, maximum performance being obtained in the vicinity of A = 8 in., and ID = 4 to 8 bits (depending upon the particular task). The average movement time was found to be directly proportional to the ID. From these results Fitts concluded that the information transmission capacity of the motor system is relatively constant over a considerable range of task conditions.

Welford (1960) reports that Crossman (1957) had produced results, which although obtained independently of Fitts', are in striking agreement with them. According to Crossman (1957), a corrected estimate of width, W, adjusted for errors should be used in computing ID.

Annett, Golby and Kay (1958) employed a similar task to one used by Fitts (1954) and found that, to obtain the proper measure of index of performance, it was necessary to use only the time for that portion of the motion which is related to the difficulty in question.

Further work by Schonten, Vredenbregt, and Andriessen (1960) has indicated that it is necessary in pin transfer tasks to take account of the absolute size of the pin as well as the tolerance between pin and hole, since the finer pins take a disproportionately long time to grasp (the task was to transfer metal pins from one set of holes to another a given distance away). This is perhaps in line with Crossman's (1957) finding that, with "small" targets, both width and height need to be taken into account.

Welford (1960) suggested that an improved index of task difficulty should be:

$$ID = \text{Log}_2 \frac{A + \frac{1}{2}W}{W} \qquad ....(7)$$

This suggestion is based in part on the observation that this definition reduces the numerical value of the first constant a, in equation (6), giving theoretical predictions of MT near zero for an ID of zero. According to Welford (1960), this formulation makes movement time (MT) dependent upon a kind of Weber-fraction in that the subject is called upon to distinguish between the distances to the far and near edges of the target. In other words, the subject is called upon to choose a distance W out of a total distance extending from his starting point to the far edge of the target, $A+W/2$. The formulation also insures that the index will never be negative, since in the extreme case when the movement begins at the edge of the target $A = \frac{1}{2}W$.

Welford plotted the data (ID versus MT) of Fitts' experiment (1954) and all the points were found to lie on a straight line - - that is, Fitts' data was more accurately represented by equation (7) than equation (4).

Ross, without evidence of validity, has suggested the following modification of Fitts' formula (Equation 4).

$$ID = \text{Log}_2 \frac{L}{W_s} \text{ bits} \qquad ....(8)$$

where,

L = Maximum extension to which movement is possible in the same direction.

W_s = Target dimension in the direction of motion.

For this expression to be applicable, the motion over the distance L must be completed within one "moment's" time. Stroud (1955) has defined moment as "An interval of human subjective time during which all stimuli received are integrated to form a single sensation." According to Stroud, this time is between 40 and 200 milliseconds. Ross further states that the expression given above adequately describes those motion performance requirements generally known as positioning, or transport and positioning.

In choice types of tasks such as light key pressing, when the subject does not know exactly what he will do in each trial, the average capacity, according to Crossman (1960), seems to be about 5 bits/second, though with very long practice, he may reach 15 to 20 bits/second. It should be noted that Crossman (1960) estimated the capacity of the human motor system in a serial task and estimation of the capacity in choice tasks is based upon the findings of Hick (1952). According to Crossman (1960), the human sensory motor apparatus is comprised of two functionally distinct parts as shown in Figure 3. The Decision Mechanism has a capacity of up to 15 or 20 bits/second in highly practised tasks although it is about 5 bits/second in most cases. The Effector Mechanism achieves about 10 bits/second for hand movements.

Kay (1962) investigated the effect of practice on the performance and transmission rate of two subjects in a pin transfer

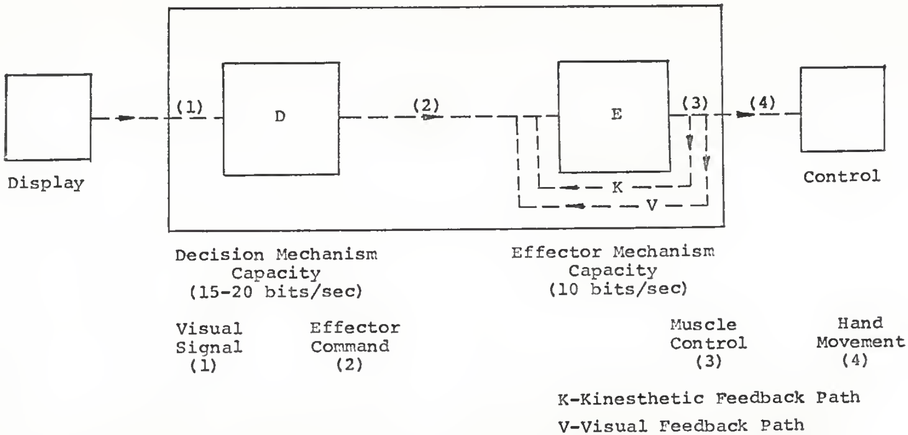
task which was similar to ones used by Fitts and Annet et. al. The transmission rate of the younger subject increased from about 10 to 20.7 bits/second and that of older subject from 10 to 17.2 bits/second after a practice session of 30 days. Kay interpreted the results from a different standpoint. The subject was able to speed up his performance, he states, not because he was transmitting more information in unit time, as the results might suggest, but because he was transmitting more signals whose variability (error) was less.

Constant motor capacity is also evident in discrete movements executed in two choice reaction time (RT) situations (Fitts and Peterson, 1964). They studied the effects of response amplitude and terminal accuracy of reaction time and movement time and found that the times for discrete movements follow the same type of law as was found earlier (Fitts, 1954) to hold for serial responses. That is

$$MT = RT + b(ID) \qquad ....(9)$$

where b = slope constant.

Fitts and Peterson further found that the information capacity of the motor system in choice tasks is rather higher than serial tasks and was found to vary from 14 bits/second, for ID = 7.5 bits (the most difficult movement studied) to just over 22 bits/second for a value of ID = 2.5 bits (the least difficult movement studied). They attribute this increase in motor capacity to the fact that processing of feed back data in serial tasks introduces some small delay as compared to the choice tasks.



The Decision(D)-Mechanism translates perceived signals into instructions for the Effector system.

The Effector(E)-Mechanism controls the muscular activity needed to carry out the instructions. It may use visual feedback, V, or kinesthetic feedback, K.

Figure 3. A schematic representation of information flow in the human perceptual motor system. (Crossman, 1960)

Konz et.al. (1967) report that their subjects processed information at a rate of 3 to 6 bits/second for tasks with ID = 12 to 36 bits/item; it should be noted that these tasks were considerably more complex than those reported by others. In conducting further experiments, Fitts (1966) found that the loss in information resulting from errors increases relatively much faster than does the gain from increased response speed and produces information overload. The presence of such a maximum load is contrary to the previous finding of a relatively constant information capacity of the human motor system over a wide range of movement accuracy (Fitts, 1954; Fitts and Peterson, 1964; Fitts and Radford, 1966).

Information theory has also been used in Industrial Engineering. A very few studies are reported and hence these will be considered in a greater detail. Rosenstein (1955) has pointed out some of the applications of information theory to Industrial Engineering. Because of its mathematical structure, Rosenstein states, information theory should prove the tool to resolve the industrial engineering problem of "capacity, production rate, system noise, and error (quality control)". Production control, quality control, time study, etc. are statistical problems while information theory is a statistical theory. According to Rosenstein, the average industrial engineer should be able to apply the theorems and concepts derived from communication theory to the industrial situation on both a macroscopic and microscopic basis. Macroscopically, the applications at

present tend to be qualitative and conceptual. Microscopically, quantitative time study applications are possible. In this connection Rosenstein mentioned in detail the studies conducted by Fitts (1954).

Ross cited the studies done by Crossman and Seymour (1957), who investigated the nature and acquisition of industrial skills. They define six stages in the acquisition of skills as:

1. Learning a sequence of activity.
2. Determining an optimum sensory channel for each stimulus. For example, at first one object might be visually observed. Later this is associated with a certain sound which gradually becomes the stimulus.
3. Achieving a sensory "set", where set can be defined as the predisposition to perform a desired response to a specified stimulus.
4. Efficient use of information. Probabilities of true stimulus are learned, less attention is given to noise, more of the input is used for decision making.
5. Sensory motor pattern is formed in true temporal relationship. Necessary information required is obtained well in advance of action to provide correct anticipation.
6. Habit develops, where whole groups of actions are triggered off by conscious observation of only a few stimuli.

They define these stages of learning as the transient stages which ultimately lead to steady state performance of the task for which they develop an analysis procedure, called sensori-motor process chart (SMP Chart).

The SMP chart is divided into category columns of: time, motion elements or therbligs, concurrent sensory channels (vision, hearing, touch, kinesthetic), perceptual processes being employed, and presence or absence of mental work.

The perceptual processes are defined as being: planning, current control, initiating and terminating, and checking. Mental work is considered to be present only if symbolic stimuli are being presented.

For each motion element the following questions are asked to determine if perceptual processes are being used:

1. Does it vary from cycle to cycle in an important way? If so, this implies planning. Plan occurs when choice occurs.
2. Is accuracy or care required in an unusual degree? If so, this implies current control. Control used for ballistic motion is not "unusual".
3. Does commencement or termination depend on an external signal or equipment performance? If so, this requires initiating or terminating.
4. Can action or product go wrong? If so, this implies checking. Check occurs when the outcome is in doubt.

While this method does not give a quantitative measure of information content, it certainly supplies a qualitative measure of what is taking place for purposes of task modification or comparison.

Crossman and Seymour also develop the feasibility of using information techniques to measure perceptual load in a task. They define perceptual load as the amount of choice in performance and the error in choice allowed by the task. Choice is measured from the number of alternatives and their likelihood. Error is determined from the number and distribution of mistakes. They also state that both difficulty of making a decision and the noise present further increase the perceptual load, but propose not to consider these factors in an analysis.

They point out that considerable data needs to be taken on the information present in typical tasks. Then the information output of other tasks may be compared with these typical ones. Their criterion for skill is the rate of performance related to the average obtained by an experienced worker for standard output and quality.

The information content of several tasks such as sewing socks (non-symbolic) was given as 13.5 bits/second and mail sorting (symbolic) as 5 bits/second, although the method of analysis was not given.

Ross advanced the proposal that information theory can be extended and expanded to provide the Industrial Engineer with a new and powerful aid in his evaluation, measurement and

synthesis of human work. He developed a decision model based on twelve information factors, which comprise virtually all of those that have an important bearing on the amount of information processed.

To determine the suitability of the information content analysis model to describe human work difficulty or complexity, several comparisons were made between difficulty as measured by information content and by more conventional measures such as performance time, or the number of errors made, etc. One test of the model involved computing the information required to be processed by an operator for a specified task and measuring the time required for performance. The task was then varied by changing the amount of information to be processed. The time for performance under these changed conditions was again noted. The results of an experiment by Crossman (1955) were expressed in information measures. The time to perform the task and the amount of information contained were plotted and a linear relationship was obtained.

In a second experiment, the information factors evaluated were the number of choices, subjective probability and equivocation. When plotted, it was found that the performance time was linearly related to the information content.

A third test of Ross' model involved the comparison between the difficulty of two tasks by computing the number of errors performed in each. Data from an experiment by Poulton (1958) were employed in this comparison. When the number of errors

made in each task were converted to information measures, they agreed very closely with the task difficulties as computed by the direct summation of the information to be processed by the operator for each task.

In a fourth analysis with the model, the information content of seven factory jobs was evaluated. These jobs were, in most cases, very lightly loaded with mental work. A comparison was made of the total information required to be processed by the operator in each job per cycle of operation. The ranking of these jobs agreed with the independent ranking made by conventional job evaluation procedures.

Typical of the job analyses which should be benefited by the information approach, Ross states, are those of a quality control inspector, a trouble shooting specialist, a pilot, and a radar observer. These jobs have two underlying aspects in common which are believed to be important to the successful use of information content analysis:

1. Reasonably well-defined stimulus response categories.
2. Work which requires mental, rather than purely physical, capacity.

Further application of the information approach to work analysis, according to Ross, can provide, first of all, a taxonomy for describing work complexity. Secondly, techniques can be developed for evaluating learning difficulty when synthesizing new tasks. And thirdly, the information approach provides criteria for evaluation of man's efforts in man-

machine systems; this, in turn, permits comparison between man and machine. Thus not only may optimum work design be expedited, but realistic rates of human activity can be established within the bounds of prescribed errors and prescribed mental and physical exertion on one hand, and boredom on the other.

In one research project at the University of Birmingham (Nadler, 1963), length of time per task did not appear to provide a direct measure of complexity, and a rough application of information theory was made to determine if this approach could provide a measure of complexity. The rough measurement did provide some discrimination, which led to the hypothesis that quantitative analysis (and thereby design) of any type of work, mental or manual, could be approached as an information processing activity.

Hart (1964) found that information theory provides a basis for selecting the most economical (in terms of time) instructional medium for electronic assembly tasks. The operator's learning for three information content levels and three instructional modes (blue print, process sheet and audio-visual instruction) was compared. The information content of the task and average cumulative minutes for the operator to achieve "standard" were plotted and the relationship was found to be linear. A nomograph (relationship between information content and the total cost of manufacturing) was also constructed and it was pointed out that a manufacturing concern can determine the optimum mode of manufacture from such nomographs. It should be noted that the

tasks employed by Hart required mental as well as purely physical effort.

Noettl and Brumbaugh (1967) used the information theory concepts in network planning. They placed the planning system in the framework of a communication system by comparing the elements of the basic model of a communication system to a planning system as illustrated in Figure 4. They further advanced the proposal that, for planning networks describing activity paths, the most critical of these paths are those with the highest uncertainty values. Furthermore, over a period of time as the network structure changes, the critical paths tend to shift in the direction of highest uncertainty. According to Noettl and Brumbaugh more consideration should be given to the application of information concepts in solving planning and controlling problems due to the increased complexity of end products and manufacturing operations.

Rathore (1968) investigated the effect of distance and direction on the speed and accuracy of single hand and two hand simultaneous motions in a reciprocating tapping task. He used Fitts' formulation to calculate the rate of performance. In simultaneous motions, the rate varied from 12.9 to 14.7 bits/second for an amplitude of 9 inches and from 11.8 to 13.7 bits/second for an amplitude of 16 inches, while in single hand motions it varied from 10 to 15.8 bits per second at 9 inches and from 14.6 to 23.2 bits/second at 16 inches. Simultaneous movements require more information to be processed than the

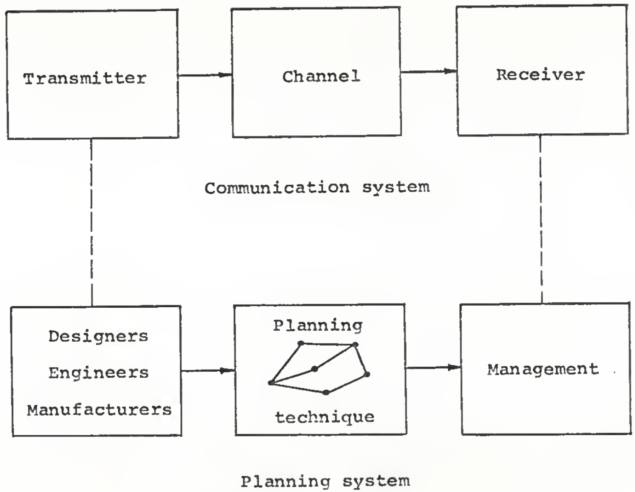


Figure 4. Communication system and planning system compared (Noettl and Brumbaugh, 1967)

single hand movements and hence the information processing rate of the motor system should be more in the former case. However, Fitts' formulation does not take this factor into account. The rates obtained in the investigation of Rathore are high when compared to other investigations. This increment in the rate can be attributed to the difference in the response. (The inner target was larger than the outer target).

In one class project at Kansas State University, Kalra and Balbale studied, in a reciprocating task, the relationship of small amplitudes (3 to 5 inches) and larger amplitudes (16 to 24 inches) to three different target sizes (¼, ½, and 1 inch diameter). They tested four different formulations for the index of difficulty. The formulation suggested by Welford was found slightly better than the other ones. A correlation of 0.99 in all the four formulations suggests the robustness of Fitts' log formulation.

As far as the author knows, no experiments are reported on the contribution of physical effort to the information content of the task. However, Ross has proposed a method for establishing a measure which might permit the more physical aspects of a task to contribute a proportionate share to the calculation of the task difficulty. This method is based on the empirical formulation derived by Ingenhol (1959) to measure the contribution to work caused by lifting or carrying loads of different weights. Ross, without evidence of validity, proposed the following expression:

$$H = K_o \text{ Log}_2 \, d(W_t/W_o)^2 \text{ bits} \qquad ....(10)$$

where H is to be calculated from

$$H = ndW_o \qquad ....(11)$$

where, n = number of cycles per unit time.

d = distance over which W_t is moved, in ft.

W_t = external load.

W_o = 22 pounds.

K_o = constant of proportionality.

Handling or transporting small weights such as one, two, or five pounds, is not a physical effort according to Ingenhol. The threshold, after which the energy consumption rapidly changes, is approximately ten kilograms and hence W_o is twenty two pounds in the above equations. It remains to be seen if K_o is truly constant over the range of interest.

Konz (1967a) has suggested an analogy of Shannon's theorem 17 for the index of difficulty for physical effort as:

$$ID_p = \text{Log}_2 \frac{W_A + W_C}{W_A} \text{ bits/response} \quad ......(12)$$

where,

ID_p = Index of difficulty due to physical effort.

W_A = Weight of the arm with which movement is made.

W_C = Weight moved.

This thesis investigated the validity of equation (12).

2. Force Platform:

The use of physiological cost to the worker as the rational basis for finding task requirements and for comparing various methods of performing a task is an inherently logical notion and has been advocated by many persons. A major difficulty in implementing the notion lay in the instrumentation for measuring physiological cost.

Greene, Morris, and Wiebers (1959) mentioned three methods of determining energy expenditure. The first two methods used direct measurement of caloric consumption as the criteria. These methods are difficult to perform; consequently, they are rarely used. The third method, an indirect estimate of calories expected, is based on the oxygen consumed. The oxygen is used in a burning process of the stored carbohydrates in the body. One problem is the time lag before the body uses the aerobic energy supply, another is the oxygen debt phenomena and a third is the high effort required before the difference between the basal oxygen and the working oxygen consumption can be distinguished. Ingenhol says that oxygen consumption crosses a threshold when the weight lifted exceeds approximately 10 kilograms (22 pounds). Below this threshold the difference between metabolism while working and the basic metabolism is not detectable by carbon dioxide measurements and the results do not give a precise account of the work being done by the operator performing the task.

Nichols and Amrine (1959) investigated some principles of motion economy using heart rate as their criterion. They assumed that a faster heart rate was associated with more effort or energy exerted. Fahnestock, et. al. (1963) point out, however,

that there is not a linear relationship between the energy and heart rate (Konz & Day, 1966). Fahnestock's subjects pedaled a bicycle ergometer at 30 RPM for several hours, and they found that the heart rate rises for approximately 30 minutes after the start of work even though a constant amount of energy is being exerted. This method, as well as the oxygen consumption method, requires appreciable physical force to be exerted.

Many of these measurements problems can be overcome by the use of the force platform. The force platform was developed by Cunningham and Brown (1952) in America and by Lauru (1953)(1957) in France, improved by Greene and Morris (1959), and further modified by Baranay (1963) and Hearn (1966). Greene (1957) found that there was no apparent relationship between the force platform data and the pulse rate. However, he found that the platform data showed a correlation of 0.79 with the caloric cost (oxygen analyzer method).

Dunnington (1961) and Hudson (1962) studied the effect of work place dimensions on the physiological cost as measured by the force platform. The task contained a variety of motions and simulated a drilling operation. Adjusting the work place to fit the subject's anthropometric measurements significantly reduced the effort (force trace) to perform the task.

Barta (1962) investigated the existence of the relationship between the external force exerted by a worker (measured by the force platform) and time. The subjects moved five boxes, weighing 0.35, 0.92, 3.92, 6.92 and 12.92 pounds, for a total distance of about 27 inches in a zig zag manner. He found that the three

components of external force, as measured by the force platform, increased at a much greater rate than the increase in time as the weight handled increased from 0.35 to 12.92 pounds.

Markstrom (1962) studied the variation of lateral orientation (direction) or sector (location) of a move in a three dimensional space. Lateral orientation produced no significant time or external force difference, while the variable sector (location) caused a significant external force difference but no time differences.

Konz and Day (1966) and Day (1965) varied the height and handle orientation of a push-pull task. The subjects operated the push-pull device at each of five handle heights (knee, hip, waist, chest or eye) with each of five handle orientations (0, 45, 90, 135, and 180 degrees). Even though the force required for the task itself did not vary, changing the height of the handle forced each subject to exert a force to maintain his own body position. This force exerted by the subject was minimized when the handle was at chest height.

Wu (1965) investigated the effect of direction of movement and height of work station. The subject moved a two-pound weight with his right hand from a central point to a peripheral point 15 inches away at 0, 45, 90, 135, and 180 degrees. Five different heights of work station were considered. He found that inward motions require greater physiological cost (measured by the force platform) than outward motions and that the most efficient movement of the right hand, for both in and out motions, is at zero degrees and the least efficient at 135 degrees.

Jeans (1966) studied the physiological cost of simultaneous and symmetrical motions. The subject moved a two pound weight in each hand between the specified points 18 inches apart under three experimental conditions. It was concluded that the output of the force platform in the lateral plane is a measure of simultaneity of the movement and that the outward motions of the hands require more force than the inward motions.

Thus, from the above studies, the output of the force platform is an acceptable index of the physiological cost of hand motions.

3. Horizontal Arm Motions:

Motion study had its beginning when Gilbreth (1911) observed the methods by which work was performed in brick laying. These first observations gradually developed into a set of "Rules for motion economy and efficiency," formulated mainly on the basis of experience but not verified by controlled experiments.

Barnes and Mundel (1939) studied the simultaneous and symmetrical motions of hands. They found that the speed of such movements is optimum when they are at angles of 60 and 120 degrees. It was also found that the angle is much more critical in terms of accuracy than in terms of speed. At a controlled rate of speed, the 90° position was the best, resulting in 29% fewer misses than the 0°, 30°, or 60° angles (0° was referred to as three o'clock position).

Barnes (1940) revised the rules of motion economy formulated by Gilbreth (1911) and formulated his own principles of motion economy by collecting the fragments of early works. Barnes (1963) clearly stated the criteria for evaluation of these principles: "These principles do, however, form a basis - a

code or a body of rules - which, if applied by one trained in the technique of motion study, will make it possible to increase greatly the output of manual labor with a minimum of fatigue."

McCormick (1964) cited a study made by Fitts (1947) in which blindfolded subjects made positioning movements in free space with the right hand. They were most accurate when their positioning was straight ahead (90 degrees), were equally accurate when positioning at 45 and 135 degrees, and least accurate when positioning at the zero or 180 degrees angle. They were slightly more accurate when reaching to the right (zero) than when reaching to the left.

Corrigan and Brogden (1948) found that the precision of constant velocity movements of the right hand is a function of angle from the body at which the movement is made. The empirical relationship is:

$$Y = a - b \text{ Cos } 2X + c \text{ Sin } 2X \quad ....(13)$$

where,

Y = Precision of right arm movements in terms of group mean frequency stylus contact.

X = Angle from the body at which the movement is made,

and a, b, and c are constants.

The study was divided into three experiments each having a different set of angles and the angle was incremented by 30 degrees. Subjects moved a metal-tipped stylus on a 0.4 cm. wide glass track positioned at different angles and the number of stylus

contacts made on the side of the track was recorded at each angle by means of an electronic counter.

Corrigan and Brogden (1949) had subjects move a stylus for 14 inches between two brass strips resting on a piece of glass. The target under the glass moved at a constant velocity. The direction of path was positioned at 15 degrees increments around a center. The movements were made by the right hand and accuracy was the criterion. Minimum errors were made at 45 and 225 degrees and maximum errors (about 40% greater than minimum) were made at 135 and 315 degrees. They also found that the trigonometric relationship, equation (13), between the precision of pursuit movements and the angle remained valid.

Brogden (1953) investigated the effect of practice on the trigonometric relationship of precision and angle of linear pursuit movements of the right hand. The task used was the same as in the previous studies. The subjects were divided into eight groups and each group was given practice on one angle only. It was found that the practice had a differential effect on angles. No learning was obtained at the angles of 90 and 120 degrees, while there were considerable differences in the amount of learning and the terminal level of performance at the other angles.

Briggs (1955) studied the effect of distance and direction on the speed and accuracy of simple repetitive movements of the right hand in the horizontal plane. The subjects moved a light stylus between targets of various sizes; the distance of move-

ment was kept at 14 inches. The movements were at angles of 0, 30, 60, and 90 degrees and the diameter of the target was 1/4", 1/2", 3/4" and 1". The criterion, a combination of speed and accuracy, was the hits in a 20 second trial. The angle at which most hits were made was 30 degrees for inward and outward motions. When the movements were towards the body there were consistently less hits than when the motion was outwards. From a fitted curve, he concluded that the best angle for outward movements was 27 degrees and for inward movements was 37 degrees.

In another experiment in which Briggs (1955) used nine angles and seven distances, the subject was required to move inward. The target diameter was kept constant at 1 inch while the direction of movement was varied from 330 to 270 degrees in 30 degree increments and the distance was varied from 7 to 35 inches in 7 inch increments. The best angle was 30 degrees and the worst was 180 degrees. Also, 210 degrees was better than 180 degrees for these right hand movements. From a fitted curve, he concluded that 19 degrees was best for distances up to 14 inches, 7 degrees was best for 21 inch movements and 336 degrees was best for 28 inch movements. The worst angle was around 170 degrees for moves up to 28 inches.

The MTM research association conducted several studies to study the effect of weight on performance (Rapheal, 1955). The research project was organized into two related but separate sections, a laboratory study and an industrial study. In the

laboratory study, a controlled laboratory operation was used to provide a sample of motion data which fitted a balanced experimental design. A large number of variables were evaluated and a fairly comprehensive qualitative description of the behavior of the moves with weight was determined. Eight subjects, four males and four females, were used. In the industrial study, a large random sample of data was drawn from actual industrial operations. This sample was used to determine weight factors and allowances, and to verify, wherever possible, the results of the laboratory study. The conclusions were:

1. An arm movement involving weight is made up of two components. These are a static component to bring the object under control of the hand and arm muscles, and a dynamic component in which the object is actually transported by the arm from one location to another.
2. The performance time of the arm movement is affected by distance of the movement. The dynamic component shows increasing time as distance increases. The static component time, however, is independent of distance of the movement.
3. The time of the arm movement is affected by the precision or control requirements of the movement. The dynamic component time increases as the control necessary for performance increases. The static component time does not seem to increase as control

increases. However, the results of this study were not conclusive concerning the static component.

4. Arm movements performed laterally either toward the body axis or away from the vertical body axis did not have any real indicated difference in times.

5. The time of an arm movement is affected by the weight involved. Both the static and dynamic components showed increasing times as the weight transported increased. However, in general, the magnitude of this increase was not as large as that due to distance or control requirements.

5A. Moving a weight with both hands controlling the object reduces materially the time of the movement. The time of a two-handed arm movement was found to be equivalent to the time of a one-handed arm movement of one half the weight of the object, distance and control being the same.

5B. Sliding an object over a surface was found to require less time than moving an object of the same weight spatially over the same distance and with the same amount of control. In sliding an object, the arm is not moving a weight equal to the weight of the object. Only the frictional resistance to sliding is being overcome. This resistance, in general, is considerably smaller than the actual weight of the object. The time necessary to overcome a given

frictional resistance over a given distance was indicated to approximate closely the time of an arm movement where a weight equal to the frictional resistance is being moved spatially over the same distance.

5C. The times of arm movements involving weight performed against and with the force of gravity were not indicated to be different. The velocity and acceleration characteristics did differ, but the times remained essentially the same.

5D. The direction of an arm movement involving weight with reference to the horizontal plane did not affect the time of the static component of the motion. It did affect the dynamic component. As the direction approached the vertical, or 90-degree angle with the horizontal, the dynamic component time increased significantly.

5E. Arm movements involving weight performed by the preferred and nonpreferred hands did not show significantly different times.

5F. Male and female performance of arm movements involving weight were significantly different. The difference in static component times increased as weight moved increased, but was not affected by the distance of the motion. The actual movement time difference remained relatively constant regardless of weight moved or distance.

5G. The time required to release the object was found to increase as the weight moved increased. This indicated that time to release muscle tension increases as the amount of tension increases.

5H. As the weight moved increases, the distance of the arm movement tends to be reduced by industrial workers. There was some indication that operators tend to keep the amount of work performed in an arm movement within a restricted range.

5I. The static component time increases approximately 0.0000037 hours per pound of weight to be moved.

5J. The dynamic component time increases approximately 1.1% per pound of weight moved over the time with negligible weight.

Welford (1958) cited several experiments on speed and accuracy of hand movements to study the effect of ageing on performance. Slowing of sensori-motor performance with age, Welford states, is due not to longer time required to execute movements as such, but to longer time needed to initiate, guide and monitor them, owing to a limitation in the capacity of central processes. Furthermore, where there is a choice open to them, older subjects appear to shift the balance between speed and accuracy toward accuracy. Such stress on accuracy does not seem to be designed to conserve the energy but rather to keep down the time taken to control action and make decisions.

Schmidtke (1958) investigated the effect of motion speed on motion accuracy. The subjects struck the target which was 40 cms. from the starting point. The speed was varied between 10 cms. and 100 cms. per second with the help of a metronome. The error (the deviation from the "bull's eye") in millimeters was recorded. The least errors were registered for the speed between 20 and 25 cms. per second.

Schmidtke and Steir (1961) reported a series of experiments to evaluate the validity of predetermined elemental time systems. In one experiment seven female subjects moved a stylus 16 inches from a center point to points at 45-degree increments. Fitting a curve to the points they estimated the angle for minimum time was 55 degrees and the angle with maximum time (about 22% more) was 145 degrees.

Lincoln and Konz(1966) studied the speed and accuracy of operating a switch and they concluded that the movements of the hand at 45 degrees were better than the movements made at 135 degrees.

Konz (1967b) investigated the effect of direction and inward versus outward motions of the right hand. The criterion was the number of pieces assembled in a pegboard-assembly task. The distance between the pegboard and the parts bin was kept at 15 inches and the pegboard was in or out at each of the three angles (45, 90 or 135 degrees). The 135 degree angle was worse than both the 45 and 90 degree angles, while there was no significant difference between 45 and 90 degrees.

Performance was 11% lower when the assembly was performed away from the operator rather than closer.

Rathore (1968) studied the effect of direction and distance of movement on single hand and two hand simultaneous movements. The task consisted of striking the targets with a stylus by making repetetive hand movements between the inner and outer targets. The criterion, a combination of speed and accuracy, was hits in a 18 second trial. Seven angles (0, 30, 60, 90, 120, and 180 degrees) and two distances (9 and 16 inches) were investigated. It was found that, in simultaneous motions, the performance improved as the spread of the angle between the hands decreased; the angle of the best response was 90°. The angle of best response for the right hand alone was found to be 60 degrees for both distances; while for the left hand alone it was 90 degrees at 9 inches and 120 degrees at 16 inches.

Thus, the literature survey has revealed the following points:

1. There is no published data of any experiment investigating the effect of physical effort on the information capacity of the human motor system.
2. Different criteria, namely physiological cost, speed and accuracy, have been used separately by different investigators to determine the optimum direction of hand movements, but no experiment is reported which compared all the three criteria in the same task. (Markstorm and Barta compared two criteria, physio-

logical cost and time while Briggs and Rathore used a criterion which is a combination of speed and accuracy.)

3. For horizontal movements at a height, the effect of inward and outward motion of hands is not clear cut.

Taking into account the above points, it was decided to test the following specific hypotheses about single hand (preferred hand) motions in the horizontal plane.

4. Hypotheses:

I The performance using each of the three following criterion measures varies with the direction of the movement and weight carried.

a) rate of performance, as measured by information techniques,

b) physiological cost, as measured by the force platform,

and c) accuracy.

II The "best" angle determined from each of the above criteria is the same.

III Inward motions are superior to outward motions from the standpoint of accuracy.

METHOD

Task: The task was similar to one used by Fitts (1954) and consisted of tapping two identical targets alternately with a metal-tipped stylus. Plate I. The diameter of the target, which established the tolerance within which the movement was to be terminated, was kept 1 inch, while the amplitude, the distance between the centers of two targets, was kept 16 inches. In order to vary the amount of physical effort to do the task, four different styli were used, their weights being .12, 1.25, 2.38, and 3.25 pounds respectively. The direction of the movement was varied from 0 to 180 degrees in increments of 30 degrees (0 degrees being defined as "three" o'clock position). The standing subject performed the task with the right hand while the physiological cost of doing the task was measured by the force platform.

Equipment:

1. Force Platform: The force platform used in this study was designed and constructed by Hearn (1966). Plate II. The forces in three perpendicular axes were recorded graphically on two two-channel oscillographic recorders. Three of the four channels were used for these forces, while the remaining one was used for the hits on the targets and error plates. Figure 5.

2. Adjustable Table: The seven angles viz. 0, 30, 60, 90, 120, 150, and 180 degrees were marked as 1, 2, 3, 4, 5, 6, and 7 respectively on the table top. The table was placed on a

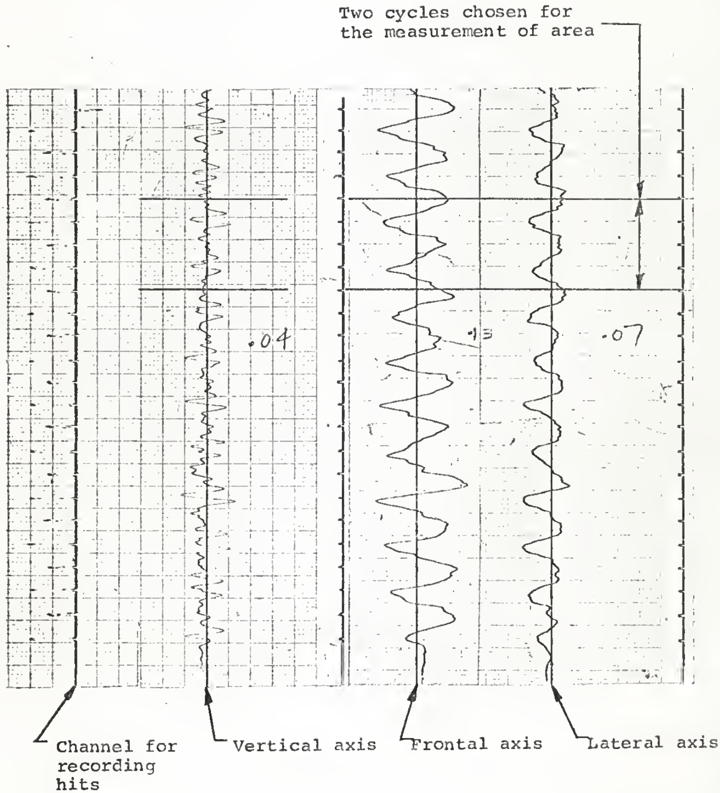
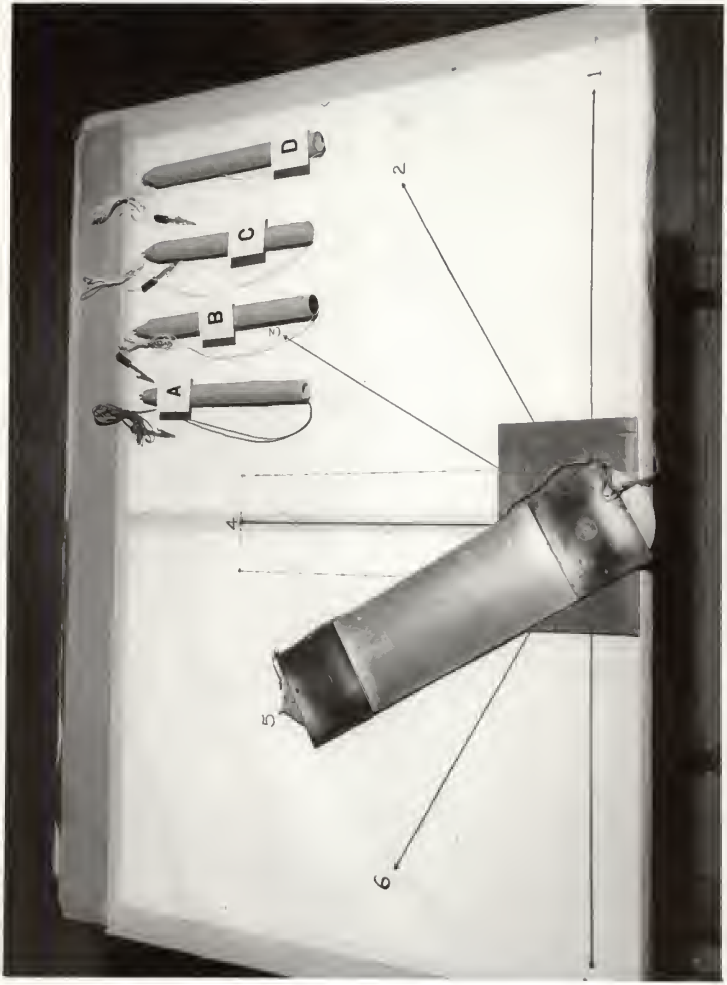
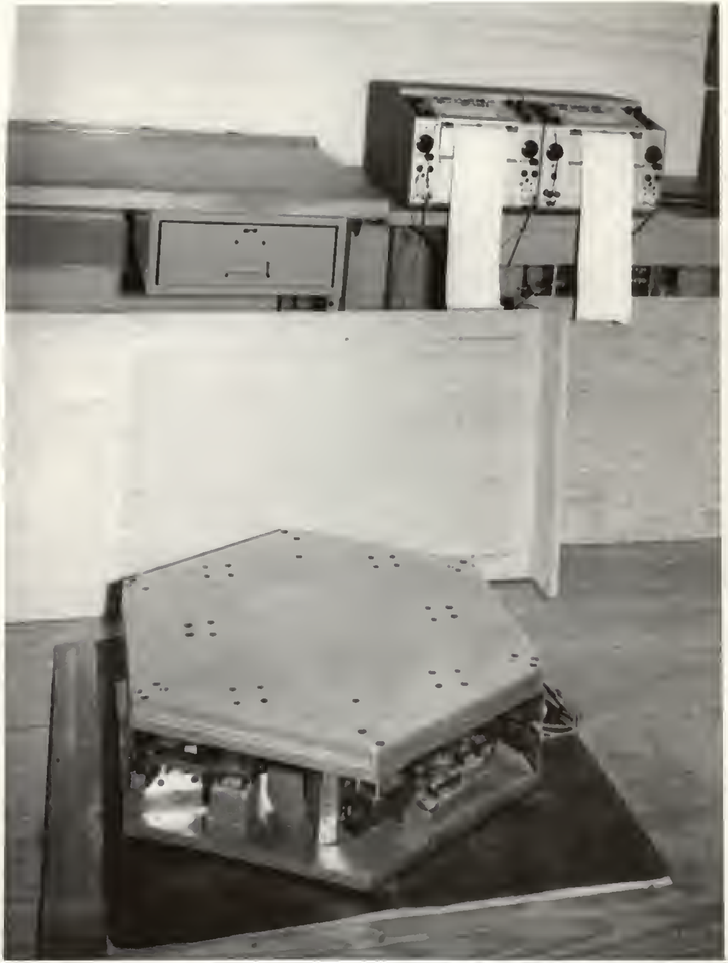


Figure 5. Output of the oscillographic recorders.


A
B
C
D
1
2
4
5
6



hydraulic lift so that it could be adjusted to the desired working height. Plate III.

3. Target Assembly Plate: Two 1 inch diameter targets with their centers 16 inches apart were mounted on a 5 x 22 inch steel plate. Each target was surrounded by a 5 x 5 inch steel plate to record errors when the target was missed. The target assembly plate was fixed on the adjustable height table in such a manner that it could pivot freely about the center of its inner target. The inner target, the outer target, and the error plates were insulated from each other and were connected to one of the two oscillographic recorders so that the number of correct hits and errors for each of the targets could be recorded separately. Figure 5. The circuit was so designed that the correct hits and errors for both the targets were recorded, respectively, on the left and right hand side of the center line. It was possible to distinguish between the hits and errors at the inner and outer targets from the length of deflection of the recording pen. In Figure 5 the longer lines are for the inner target and the short ones are for the outer target.

4. Styli: Four 1 inch diameter x 11 inches long styli were used. The front (1.5 inches) end of each styli was tapered and brass-tipped. The weights of the styli were .12, 1.25, 2.38, and 3.25 pounds. These are referred to as A, B, C, and D respectively in Plate I. Each stylus, whenever used, was connected to the oscillographic recorder to get the correct number of hits.

The use of one of these four styli permitted the amount of physical effort to be varied without otherwise changing the task.

5. Steel Tape: A steel tape in 1/2-inch increments was used for taking the anthropometric measurements of the subject.

6. Weighing Scale: This instrument was required for taking the subject's weight.

7. Stop-Watch: A decimal minute stop-watch was used for timing the trial and rest periods.

8. Planimeter: A planimeter was used to measure the area on the chart paper.

Subjects: Eight right-handed male graduate students were paid by the hour. Table 1. Their ages varied from 21 to 28 years; their heights from 62 to 70 inches and their weights from 104 to 160 pounds.

Experimental Procedure: There were seven angles and four styli, thereby making a total of 28 conditions. Each subject performed one trial at each condition during the practice session and two trials at each condition during the experimental session. The sequence for styli was so arranged as to balance the effect of learning, while that for angles was randomized. Table 2.

In view of the individual physiological differences, the height of the work station was adjusted to 1 inch below the elbow for each subject (Konz, 1967b). The distance between the center of the inner target and the front edge of the table was kept 4 inches (Barnes, 1963).

Table 1

Personal data for subjects

Subject	Major	Age, Years	Height, Inches	Weight, Pounds	Forearm Arm Length, Inches	Upper Arm Length, Inches	Elbow Height, Inches
1	Arch.	27	62	104	17	13	37.5
2	Ind.Eng.	25	67	155	18	13	42
3	Ind.Eng.	28	70	148	19	16	42.5
4	Ind.Eng.	22	70	160	19	14.5	43.5
5	Mech.Eng.	22	68	127	19	14	43
6	Mech.Eng.	24	65	137	18.5	13	40.5
7	Ind.Eng.	21	68	146	18.5	14	42.5
8	Ind.Eng.	23	65	130	17.5	13.5	40

Table 2

Experimental sequence

Subject	1^{st} Replication							2^{nd} Replication						
1.	A5	A4	A7	A1	A6	A3	A2	D6	D7	D2	D3	D5	D4	D1
	B7	B1	B6	B4	B2	B5	B3	C4	C2	C5	C6	C7	C1	C3
	C3	C4	C5	C1	C6	C2	C7	B1	B6	B4	B2	B7	B3	B5
	D7	D5	D4	D3	D2	D6	D1	A6	A7	A3	A5	A1	A2	A4
2.	B6	B1	B5	B4	B3	B2	B7	A4	A1	A2	A7	A5	A3	A6
	C7	C4	C6	C2	C1	C3	C5	D5	D3	D7	D2	D6	D4	D1
	D1	D5	D4	D7	D3	D6	D2	C2	C7	C3	C5	C4	C1	C6
	A2	A6	A1	A4	A5	A7	A3	B3	B7	B5	B6	B4	B2	B1
3.	C2	C5	C4	C7	C1	C3	C6	B1	B7	B5	B2	B6	B3	B4
	D5	D3	D6	D2	D4	D1	D7	A2	A7	A5	A6	A1	A4	A3
	A7	A2	A3	A4	A5	A6	A1	D1	D2	D7	D3	D4	D6	D5
	B4	B3	B6	B5	B7	B1	B2	C5	C4	C2	C1	C3	C7	C6
4.	D5	D3	D2	D7	D4	D6	D1	C7	C5	C4	C3	C6	C1	C2
	A6	A4	A7	A2	A5	A3	A1	B1	B7	B5	B3	B6	B2	B4
	B2	B5	B6	B1	B3	B4	B7	A3	A6	A2	A4	A1	A5	A7
	C3	C2	C7	C6	C1	C4	C5	D4	D6	D3	D1	D5	D7	D2
5.	D3	D5	D1	D2	D6	D4	D7	A6	A2	A7	A5	A4	A1	A3
	C1	C2	C5	C6	C4	C3	C7	B5	B1	B6	B7	B2	B4	B3
	B6	B4	B3	B2	B5	B7	B1	C3	C7	C4	C5	C6	C2	C1
	A2	A7	A5	A6	A1	A3	A4	D7	D4	D2	D3	D5	D1	D6
6.	C5	C4	C7	C3	C1	C2	C6	D6	D7	D5	D4	D3	D2	D1
	B6	B4	B7	B2	B5	B1	B3	A4	A6	A2	A3	A1	A5	A7
	A1	A3	A6	A5	A4	A7	A2	B1	B6	B3	B5	B2	B7	B4
	D3	D2	D5	D4	D7	D1	D6	C5	C7	C1	C6	C3	C4	C2
7.	B1	B2	B5	B6	B4	B7	B3	C6	C7	C1	C2	C3	C5	C4
	A4	A7	A3	A5	A6	A2	A1	D2	D4	D7	D5	D6	D3	D1
	D4	D3	D1	D7	D5	D6	D2	A4	A3	A5	A1	A7	A6	A2
	C3	C5	C6	C4	C2	C1	C7	B3	B6	B2	B4	B1	B5	B7
8.	A4	A7	A6	A2	A1	A3	A5	B3	B5	B4	B1	B2	B6	B7
	D1	D5	D2	D6	D7	D4	D3	C6	C2	C3	C4	C7	C5	C1
	C7	C3	C1	C4	C6	C2	C5	D4	D7	D6	D5	D1	D3	D2
	B3	B6	B1	B7	B5	B2	B4	A2	A3	A5	A6	A4	A1	A7

where:

1 - 0°	5 - 120°	A - 0.12 pound stylus
2 - 30°	6 - 150°	B - 1.25 pound stylus
3 - 60°	7 - 180°	C - 2.38 pound stylus
4 - 90°		D - 3.25 pound stylus

The experiment was conducted in the Human Engineering Laboratory of the Industrial Engineering Department. As the subject entered the laboratory, his personal data such as name and age were recorded. Table 1. Next, the following anthropometric measurements were taken:

1. Height
2. Upper arm length
3. Fore arm length
4. Elbow height
5. Weight

The subject was then asked to stand on the force platform and the height of the work table was adjusted to 1 inch below the elbow. The subject was directed to stand as close to the work table as was comfortable to him, care being taken that his feet were inside the red hexagon marked on the force platform. The position of his shoes was marked on the platform so that he could stand in the same manner after every rest period. The following written instructions were then given to the subject:

> "In this experiment you are required to make a series of hand-arm movements involving weights. Your task is to hit the targets alternately with the stylus as fast and as accurately as you can. If you hit the outside plate, an error will be recorded. The positions of the targets will change from trial to trial and you will be using four different styli.
>
> Stand erect close to the edge of the work table and grasp the stylus with the thumb, fore-finger, and middle finger of your right hand. You have to use your right hand only while the left hand will be at your side. Start tapping as soon as you hear the signal "Go". The target in front of you has always to be struck first. Continue tapping until you hear the signal "Stop". Be

> sure to hit the target every time. Also, be careful not to shift your body, and your feet in particular, to any new position, once you have started tapping."

In addition to these instructions, the task was explained with demonstrations and questions, if any, were answered.

Before starting the task, the subject had a practice session of 28 trials (one trial for each condition). The object of this session was to adjust the speed and improve the performance. No data were recorded during the practice session.

Before starting the experimental session, all the three axes of the force platform were adjusted. This was accomplished by adjusting the pens on the recorders to an initial zero position, while the subject was standing on the platform with his right hand in the grasping position and the left hand at his side. The adjustment balanced out the effect due to the subject's weight.

The subject was then given the experimental session, during which he performed two trials at each condition. The number of trials performed and the rest periods given to each subject were as follows:

Practice Session:	<u>28 trials</u> (one trial at each angle and stylus)
	3 minutes rest after 14 trials
	5 minutes rest after the completion of practice session.
Experimental Session:	<u>56 trials</u> (two trials at each angle and stylus)
	3 minutes rest after every 14 trials
	5 minutes rest after 28 trials.

After every rest period, the axes were adjusted and it was made sure that the subject's shoes were in the same position. Each trial consisted of 12 seconds followed by a rest period of about 5 seconds (the time required to change the angle of the target assembly plate). The subject required approximately two hours to perform the experiment. Plate III shows a subject doing the task.

Whenever the subject failed to hit either of the targets, the particular trial was repeated. In cases where both the correct hit and error were recorded for one single hit, the total number of such hits was divided equally as correct hits and errors.

EXPERIMENTAL DESIGN

Criterion Measures: Three different criteria were used in this experiment.

1. Rate of Performance: The Index of difficulty, ID, for the task of this experiment was calculated from Fitts' formula mentioned earlier

$$ID = \text{Log}_2 \frac{A}{W/2} \qquad ....(4)$$

For A = 16 inches and W = 1 inch, ID was found to be 5 bits. The index of performance, I_p, was calculated by dividing the ID by the time required to make one movement from inner to outer target. Thus, if N is the total number of hits and errors for inner and outer targets during a trial of T seconds, then the time, t, required for one movement is given by

$$t = \frac{T}{N - 1} \text{ seconds}$$

Then, the index of performance is given by

$$I_p = \frac{ID}{t} \text{ bits/second} \qquad ....(5)$$

For a constant value of ID, the I_p is inversely proportional to the time per movement and, consequently, is directly proportional to the speed of the movement. However, the conclusions arrived at from the analysis of I_p should not necessarily hold true for the speed of the movement, because there will be difference in the magnitudes of speed, time, and I_p.

2. Accuracy: Due to individual differences, there was a great difference among the response scores of the subjects. As such it was decided to convert the data to a common base by calculating the percent correct response score for each trial. Thus if n is the total number of correct hits and m is the total number of missed hits for inner and outer target during a trial, then the percent correct response score, P, is given by:

$$P = \frac{n}{n + m}(100)$$

The percent correct response score was calculated separately for in and out motions and the difference (in-out) was used for the statistical analyses.

3. Force-time: Every time the stylus made contact with either of the targets or the error plates, the micro switches on both the recorders made marks on the chart paper. Thus it was possible to determine the number of cycles completed in one trial. In view of the considerable time required for measuring the force-time areas of all the cycles in a trial, it was decided to select two cycles from each trial. The two cycles preceding the last two cycles were chosen for this purpose. There was no specific reason for this choice. As a matter of fact any two cycles except the first few ones would have served the purpose. The subject attains his pace after the first few cycles.

Figure 5 shows the force-time traces and the hits for subject 1 at 180 degrees with the light stylus. The area of the two cycles was found by a planimeter that read in square

inches. These areas were then multiplied by the scale factors for each axis:

Frontal axis = 1 square inch = 18.43 pound-seconds

Lateral axis = 1 square inch = 21.50 pound-seconds

Vertical axis = 1 square inch = 32.25 pound-seconds

The physiological cost for doing the task was obtained by arithmetically adding the pound-second values for the three axes. In order to compare the physiological cost on a common base the total pound-second value for two cycles was divided by 4 since there were 2 movements in each cycle. The resulting value was then the physiological cost per movement. These data were used for the statistical analyses.

Statistical Design: A three factor, twice replicated, completcly randomized mixed model was used to test hypotheses I and II. The model was as follows:

$$Y_{ijkl} = \mu + S_i + St_j + A_k + SSt_{ij} + SA_{ik} + StA_{jk} + SStA_{ijk} + e_{ijkl}$$

where Y = Performance (rate of performance, percent correct response score, force-time, or percent in minus out correct response as the case may be).

μ = True mean of the over all performance

S = Effect due to subjects

St = Effect due to styli

A = Effect due to angles

i = Number of levels of subjects

j = Number of levels of styli

k = Number of levels of angles

l = Number of replications

e = Effect due to experimental error

RESULTS

The performance data obtained from each of the three criteria, rate of performance in bits/sec., arithmetic sum of force-times in three axes in pound-seconds, and percent correct response score, are shown in Tables 3, 6, and 9 respectively. A three-way analysis of variance was used to analyze the data from each criterion measure and the results are shown in Tables 4, 7, and 10.

The main effects of subjects, styli, and angles were found significant ($p < .01$) in all the three analyses. The subjects x styli and subjects x angles interactions were significant for rate of performance and force-time. No interaction was found significant in the case of percent correct response score. A Duncan's New Multiple Range Test was used ($\alpha < .05$) to test the significance of differences between means. Tables 5, 8, and 11.

The rate of performance for each of the four styli was significantly different from each other. It decreased consistently from 12.0 to 10.0 bits/sec. as the weight carried increased from .12 to 3.25 pounds. Figure 7 supports the above conclusion. For the four weights considered in this study, the rates with 1.25, 2.38, and 3.25 pounds styli were, respectively 7.1, 13.1, and 16.4% less than that with .12 pound styli. On the average, the rate of decrement in performance was 0.64 bits/sec. per extra pound of weight carried.

The highest rate of 11.6 bits/sec. was obtained at 30° while 180° was the worst - 9.9 bits/sec. As can be seen from

Table 3

Index of performance in bits/sec. at each combination of stylus and angle for each of the eight subjects.*

Subject	Stylus, lbs	0	30	60	90	120	150	180	Average
1	0.12	11.04	11.46	11.24	11.66	11.04	10.41	10.00	10.98
2		10.00	10.42	9.58	9.38	9.38	8.76	8.34	9.41
3		13.74	13.33	13.13	12.91	12.50	12.50	11.45	12.79
4		10.00	10.63	10.83	10.63	9.17	10.00	8.75	10.00
5		13.33	13.95	12.28	12.71	12.29	10.84	11.67	12.44
6		15.02	16.25	15.63	16.45	15.23	13.12	12.92	14.94
7		9.80	11.24	11.46	11.66	10.83	10.00	9.80	10.68
8		15.85	16.04	16.45	13.95	13.74	12.91	12.28	14.46
Average		12.35	12.91	12.58	12.42	11.77	11.07	10.65	
1	1.25	9.58	10.62	10.84	10.62	10.62	9.79	10.00	10.30
2		10.20	9.79	10.22	9.79	9.59	8.96	8.96	9.64
3		11.46	13.13	11.67	11.88	12.50	11.67	11.46	11.97
4		9.38	10.62	8.96	9.38	8.96	9.17	8.33	9.26
5		11.87	11.67	12.28	11.04	11.04	10.83	10.00	11.25
6		14.16	14.16	13.96	13.33	13.33	11.67	12.08	13.24
7		8.96	10.00	10.00	10.63	10.20	9.38	8.74	9.70
8		15.20	14.58	14.16	13.33	12.71	12.71	11.88	13.51
Average		11.35	11.82	11.51	11.25	11.12	10.52	10.18	
1	2.38	8.96	9.58	9.58	9.58	9.38	9.17	9.58	9.41
2		8.55	9.38	8.55	8.54	8.55	8.34	8.33	8.60
3		11.87	12.29	11.45	10.63	11.46	11.26	10.00	11.28
4		9.17	9.59	9.79	8.96	8.54	8.55	8.12	8.95
5		12.30	11.67	11.26	10.62	11.45	10.81	9.38	11.07
6		12.08	13.18	12.92	12.71	10.83	11.45	11.26	12.14
7		8.12	8.55	9.79	9.17	9.79	8.75	7.92	8.87
8		13.12	14.58	13.33	12.70	12.50	12.08	11.45	12.82
Average		10.52	11.17	10.83	10.36	10.31	10.05	9.50	
1	3.25	9.37	8.96	9.38	9.38	9.38	8.96	8.96	9.19
2		7.08	8.33	8.55	8.54	7.50	7.91	7.09	7.85
3		10.62	11.04	11.67	10.42	11.04	10.42	10.21	10.77
4		8.75	8.96	8.54	7.71	8.34	8.12	8.33	8.39
5		10.62	11.44	10.63	11.87	11.24	10.61	9.58	10.86
6		13.54	13.54	12.91	12.70	11.67	11.67	10.63	12.38
7		8.34	8.96	8.75	8.55	9.38	8.33	8.13	8.63
8		12.08	13.13	12.71	12.50	11.04	11.26	10.62	11.90
Average		10.05	10.54	10.39	10.21	9.95	9.66	9.19	
Grand Average		11.07	11.61	11.33	11.06	10.79	10.33	9.88	

Column headings: Angle, degrees (0–180); rows: Subject, Stylus, lbs.

* The index of performance is calculated by Fitts' formula unless otherwise specified.

Table 4

Analysis of variance of index of performance

Source	df	MS	F
Subjects	7	170.95	247.75**
Styli	3	84.74	65.58**
Angles	6	23.18	17.56**
S x St	21	1.29	1.86*
S x A	42	1.32	1.91**
St x A	18	0.40	0.88
S x St x A	126	0.46	0.66
Residual	224	0.69	
Total	447	-	-

* $p < .05$

** $p < .01$

Table 5

Results of DNMR Test as applied to the mean index of performance (bits/sec.)

1. Mean index of performance averaged over angles

Rank	1	2	3	4
Stylus, lbs	0.12	1.25	2.38	3.25
Index of Performance, bits/sec.	11.96	11.11	10.39	10.00

2. Mean index of performance averaged over styli

Rank	1	2	3	4	5	6	7
Angle, degrees	30	60	0	90	120	150	180
Index of Performance, bits/sec.	11.61	11.33	11.07	11.06	10.79	10.33	9.88

Note: Scores underlined by the same line are not significantly different ($\alpha < .05$)

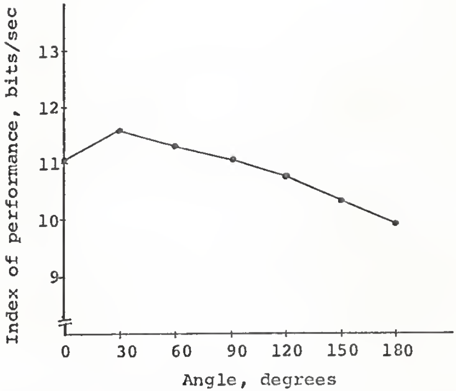


Figure 6. Effect of angle on index of performance

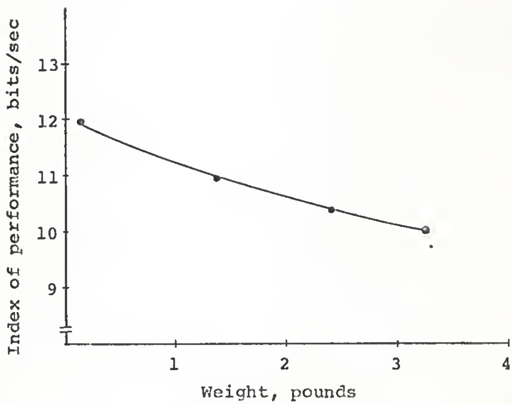


Figure 7. Effect of weight on index of performance

Figure 6, the performance decreased as the angle increased from 30° to 180°, there being no difference between the performances at 0° and 90°. There was a significant difference between the rates at 0° and 180°. The mean rate of performance was not significantly different for zero and 60°, though 60° was also not significantly different from 0° and 90°. On the average movements from center to the right were 12% better (in terms of rate of performance) than those from center to the left. Since the styli x angles interaction was nonsignificant, the conclusions regarding the angles are true for all the styli and vice-versa. This is also confirmed by the consistency of curves in Figures 8 and 9.

The physiological cost for each of the four styli was significantly different from each other. As expected, it increased from 1.89 to 2.89 pound-seconds as the weight increased from .12 to 3.25 pounds. Figure 11 shows that the increments were consistent. The percent increases in force-time above the light stylus were 7.4, 28.6, and 53.0% for the 1.25, 2.38, and 3.25 pounds styli respectively. On the average the rate of increment in the force-time was 0.32 pound-seconds per extra pound.

Zero and 30° required significantly less physiological cost than the other angles. Sixty was not significantly different from 90°, although there was not any significant difference in 90°, 120°, 150° and 180°. Zero required the least physio-

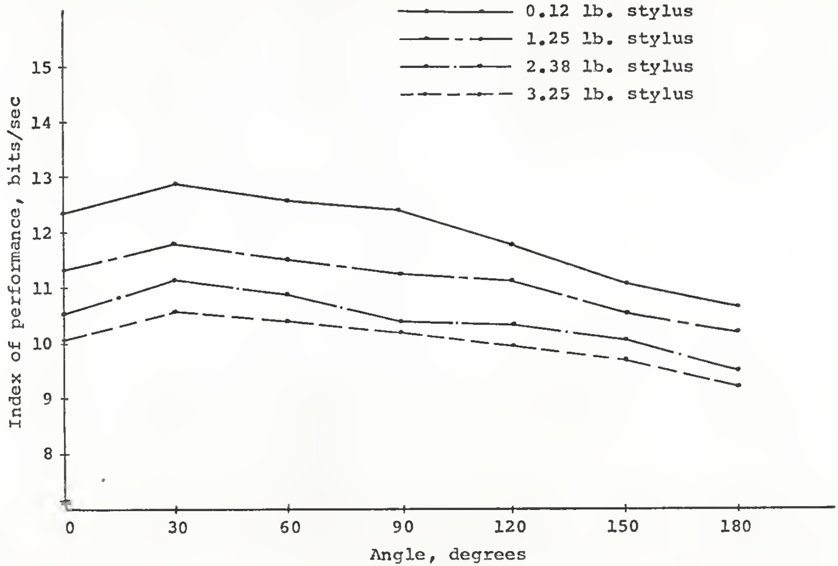


Figure 8. Effect of angle on index of performance at each of the four weights

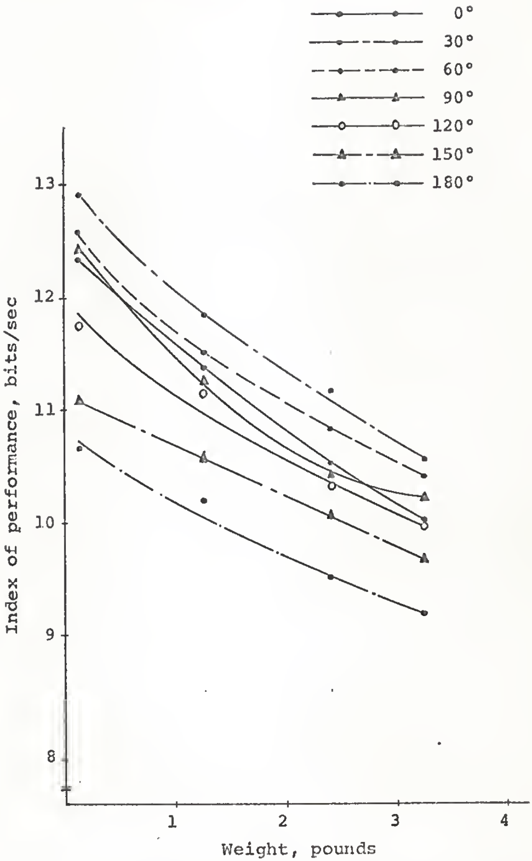


Figure 9. Effect of weight on index of performance at each of the seven angles

Table 6

Force-time in pound-seconds per movement at each combination of stylus and angle for each of the eight subjects

Subject	Stylus, lbs	0	30	60	90	120	150	180	Average
1	0.12	0.72	1.44	1.53	1.47	1.76	2.17	1.65	1.53
2		1.24	1.66	2.16	2.26	2.31	2.31	1.83	1.96
3		1.02	1.12	1.53	1.53	2.38	1.95	1.93	1.64
4		1.66	1.89	2.89	3.61	4.40	3.81	3.71	3.14
5		1.14	1.43	1.57	2.86	2.88	2.98	3.23	2.30
6		0.93	1.22	1.34	1.24	1.33	2.08	2.16	1.47
7		1.05	1.56	1.53	1.55	2.18	2.49	2.17	1.79
8		0.89	0.91	0.94	1.19	1.62	1.79	1.60	1.27
Average		1.08	1.40	1.68	1.96	2.36	2.44	2.28	
1	1.25	1.63	1.32	1.47	1.95	2.12	2.78	2.57	1.98
2		1.19	1.63	1.91	2.03	1.93	1.50	1.48	1.66
3		1.31	1.29	1.38	1.88	1.65	1.87	1.97	1.62
4		1.35	1.92	3.01	3.17	4.28	3.19	2.90	2.83
5		1.19	1.59	2.26	3.57	4.26	4.65	3.05	2.94
6		1.29	1.22	1.34	1.85	2.49	2.65	2.64	1.92
7		1.72	2.06	1.74	2.20	2.27	2.04	2.60	2.09
8		1.17	0.71	1.02	1.19	1.26	1.46	1.72	1.22
Average		1.35	1.47	1.76	2.23	2.53	2.52	2.36	
1	2.38	1.61	1.83	2.08	2.09	2.61	2.75	2.52	2.21
2		1.30	1.58	2.67	2.37	2.14	1.92	2.01	2.00
3		1.83	1.58	1.84	2.17	2.05	2.36	2.72	2.08
4		1.82	1.96	2.76	3.19	4.04	4.04	2.97	2.97
5		1.03	2.32	3.42	3.82	4.19	4.71	3.13	3.31
6		2.02	2.14	2.37	2.41	2.97	3.09	3.88	2.69
7		2.68	2.04	2.21	3.13	3.10	2.62	3.23	2.71
8		1.33	0.70	1.04	1.17	1.93	1.87	2.21	1.46
Average		1.78	1.77	2.30	2.54	2.88	2.92	2.83	
1	3.25	2.34	2.12	2.64	2.20	3.23	3.46	2.96	2.70
2		2.46	2.56	2.35	2.27	2.10	1.67	2.37	2.25
3		2.86	2.15	1.90	1.75	2.61	2.23	3.01	2.36
4		2.66	3.33	3.38	4.14	4.10	4.80	4.66	3.86
5		2.37	2.13	4.26	4.61	5.35	4.82	4.14	3.95
6		1.96	2.27	2.50	2.74	3.08	3.60	4.09	2.89
7		2.45	2.38	2.94	3.13	3.85	3.36	2.91	3.00
8		1.75	1.72	1.89	2.14	2.33	2.46	2.63	2.13
Average		2.35	2.33	2.73	2.87	3.33	3.30	3.35	
Grand Average		1.64	1.74	2.19	2.40	2.71	2.77	2.79	

Column header: Angle, degrees (0–180) and Average.

Table 7

Analysis of variance of force-time

Source	df	MS	F
Subjects	7	19.22	99.58**
Styli	3	22.87	27.75**
Angles	6	15.20	13.10**
S x St	21	0.82	4.27**
S x A	42	1.16	5.99**
St x A	18	0.09	0.43
S x St x A	126	0.20	1.02
Residual	224	0.19	
Total	447		

** $p < .01$

Table 8

Results of DNMR Test as applied to the
mean force-time per movement (pound-seconds)

1. Mean force-time averaged over angles

Rank	1	2	3	4
Stylus, lbs.	3.25	2.38	1.25	0.12
Force-time, lb-secs	2.89	2.43	2.03	1.89

2. Mean force-time averaged over styli

Rank	1	2	3	4	5	6	7
Angle, degrees	150	120	180	90	60	30	0
Force-time, lb-secs	2.79	2.77	2.71	2.40	2.19	1.74	1.64

Note: Force-times underlined by the same line are not significantly different ($\alpha < .05$).

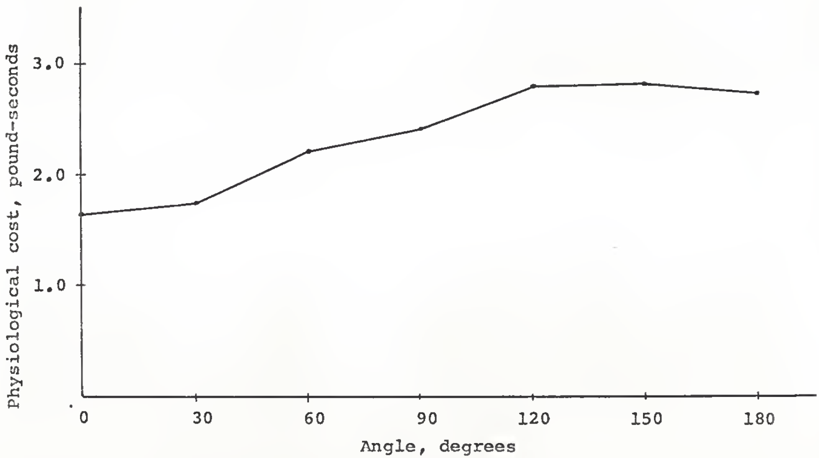


Figure 10. Effect of angle on physiological cost

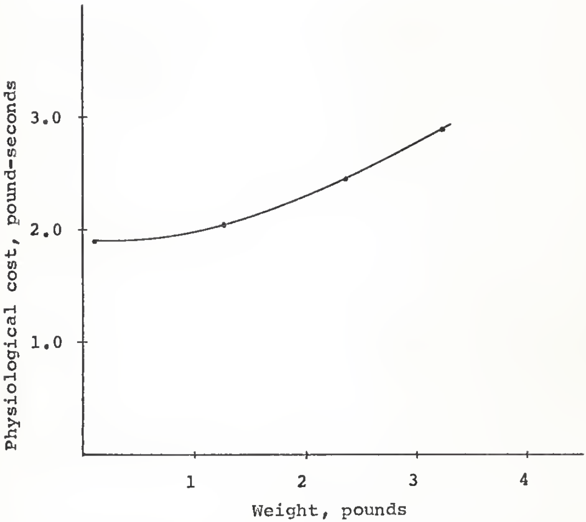


Figure 11. Effect of weight on physiological cost

logical cost, 1.64 pound-seconds, while 150° required the maximum, 2.79 pound-seconds; a difference of 69.5% (1.64 base). The above results are graphically shown in Figure 10. Movements to the left of the center required 65.0% more physiological cost than those to the right of the center. These conclusions are unaffected by weight on account of the nonsignificance of styli x angles interaction. This is evident from Figures 12 and 13.

The percent accuracy with the light stylus was significantly less than with the remaining three styli. There was not any significant difference in the accuracy with 1.25, 2.38 and 3.25 pounds styli, although responses with the 2.38 styli were most accurate. The accuracy by stylus varied from 92.0 to 94.5%. Figure 15 shows that accuracy increased with increase in weight carried. On the average, responses with the 1.25, 2.38, and 3.25 pounds styli were, respectively, 2.50, 2.72, and 2.10% more accurate than those with the light stylus. Thus accuracy was least with the light stylus and it was fairly constant with the heavy styli.

Responses at 150° and 180° were significantly more accurate than those at the remaining five angles. As can be seen from Figure 14, the 150° angle had the maximum accuracy, 95.4%, and 90° and 120° had the least accuracy, 92.9%, though there was no significant difference in 0°, 30°, 60°, 90° and 120°. Motions to the left of the center were 1.1% more accurate than those to the

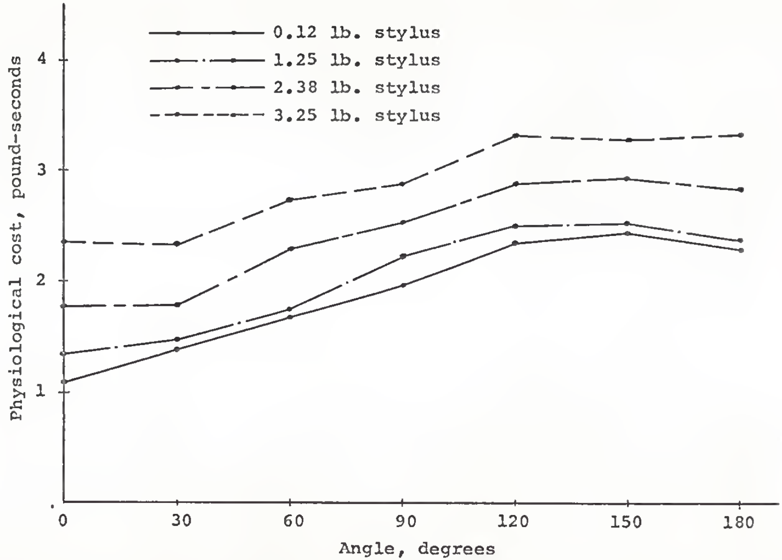


Figure 12. Effect of angle on physiological cost at each of the four weights

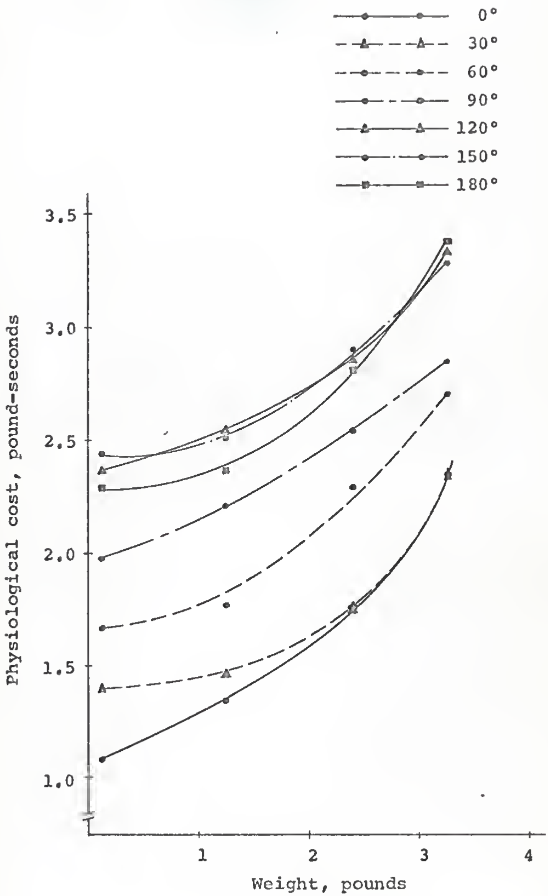


Figure 13. Effect of weight on physiological cost at each of the seven angles

Table 9

Percent correct response score at each combination of stylus and angle for each of the eight subjects

Subject	Stylus, lbs	0	30	69	90	120	150	180	Average
1	0.12	96.3	100.0	96.2	100.0	89.0	91.9	95.8	95.6
2		100.0	100.0	100.0	100.0	97.8	100.0	100.0	99.6
3		90.9	95.3	95.3	98.4	96.6	94.9	94.6	95.2
4		95.8	92.3	97.9	90.0	91.0	98.0	90.4	93.6
5		80.0	82.0	86.0	73.7	89.6	100.0	83.8	84.9
6		87.4	82.0	87.9	60.8	84.9	81.1	91.9	82.3
7		96.0	93.6	90.8	88.3	88.9	96.0	85.7	91.2
8		96.2	95.0	96.2	96.0	90.8	80.7	92.0	93.6
Average		92.8	92.4	93.8	88.3	91.1	94.0	91.8	
1	1.25	100.0	96.0	100.0	88.3	90.3	100.0	100.0	96.3
2		100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3		96.3	88.8	96.5	100.0	93.3	100.0	98.2	96.2
4		84.7	94.0	92.9	91.1	90.6	95.4	97.3	92.3
5		93.1	89.3	86.2	94.4	90.6	97.9	85.4	90.9
6		82.2	83.9	85.1	81.5	85.9	98.2	84.4	85.9
7		100.0	95.4	93.5	93.1	97.8	97.8	95.6	96.2
8		91.7	98.6	98.4	96.8	90.4	98.3	100.0	96.3
Average		93.5	93.3	94.1	93.2	92.4	98.5	95.1	
1	2.38	97.7	97.8	93.3	97.7	100.0	100.0	100.0	98.0
2		100.0	97.9	97.5	97.3	100.0	100.0	100.0	98.9
3		96.4	90.3	94.6	100.0	92.6	98.1	100.0	96.0
4		97.8	97.6	95.6	95.6	92.8	87.5	94.7	94.5
5		83.1	83.6	87.0	86.2	89.2	86.5	86.7	86.0
6		91.5	91.0	86.9	92.1	94.3	93.1	94.3	91.9
7		90.0	100.0	89.4	95.6	93.7	100.0	92.2	94.4
8		93.9	91.4	96.7	100.0	95.0	100.0	92.1	95.7
Average		93.8	93.7	92.6	95.6	94.7	95.6	95.1	
1	3.25	97.7	95.3	90.9	90.9	97.7	100.0	100.0	96.0
2		100.0	97.5	100.0	97.3	100.0	100.0	100.0	99.2
3		98.0	100.0	94.6	95.9	98.0	98.0	97.9	97.5
4		93.1	88.1	95.0	100.0	89.8	87.0	95.2	92.6
5		78.3	83.8	80.5	87.7	80.0	82.2	89.2	83.1
6		89.3	89.5	95.2	88.8	87.3	85.9	92.0	90.0
7		97.6	93.1	100.0	95.0	93.1	97.7	97.6	96.3
8		95.0	95.1	94.9	98.3	100.0	98.1	92.2	96.2
Average		93.6	92.8	93.9	94.3	93.2	93.6	95.5	
Grand Average		93.4	93.1	93.6	92.9	92.9	95.4	94.4	

(Column headings 0–180: Angle, degrees)

Table 10

Analysis of variance of percent correct response score

Source	df	MS	F
Subjects	7	0.122	4.46**
Styli	3	0.025	5.95**
Angles	6	0.012	5.70**
S x St	21	0.004	1.57
S x A	42	0.002	0.74
St x A	18	0.001	0.39
S x St x A	126	0.003	1.26
Residual	224	0.003	
Total	447	-	-

** $p < .01$

Table 11

Results of DNMR Test as applied to the mean percent correct response score

1. Mean percent correct score averaged over angles

Rank	1	2	3	4
Stylus, lbs	2.38	1.25	3.25	0.12
Mean percent correct score	94.5	94.3	93.9	92.0

2. Mean percent correct score averaged over styli

Rank	1	2	3	4	5	6	7
Angle, degrees	150	180	60	0	30	120	90
Mean percent correct score	95.4	94.4	93.6	93.4	93.1	92.9	92.9

Note: Scores underlined by the same line are not significantly different ($\alpha < .05$)

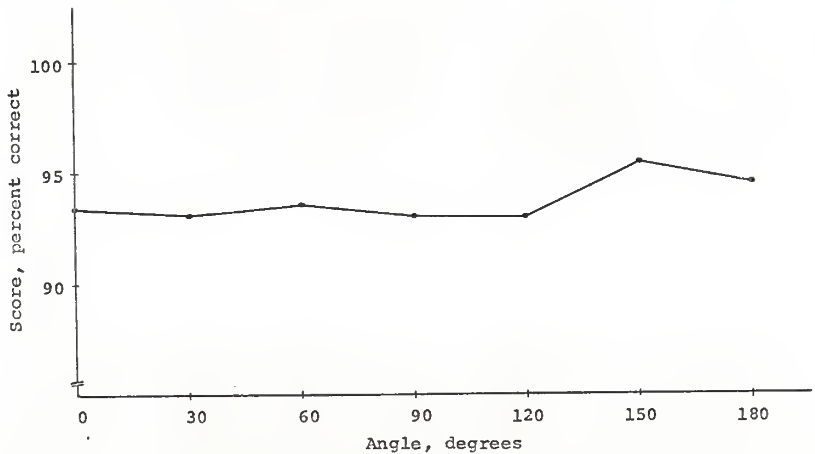


Figure 14. Effect of angle on percent accuracy

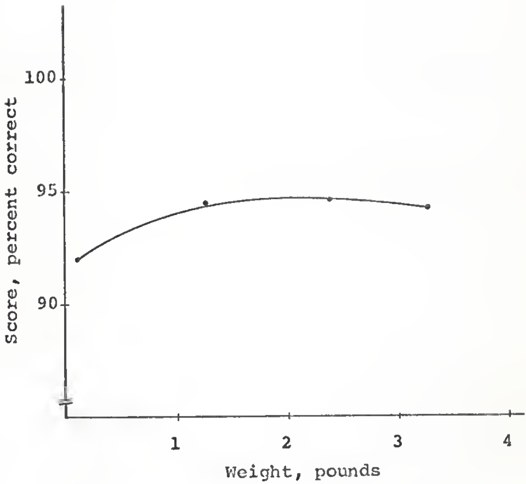


Figure 15. Effect of weight on percent accuracy

right of the center. Again, the above conclusions hold good for all the weights, since styli x angles interaction was not significant. Figures 16 and 17, however, do not support the preceding statement; it seems that there was a little interaction, the magnitude of which was not statistically significant.

Table 12 summarizes the mean values of rate of performance, physiological cost, and percent correct response score at each combination of angle and stylus and "best angles" determined from each of the above criterion measures are compared in Table 13.

Thus, the results did prove hypothesis I; that weight and direction had a significant effect on the performance measured by three independent criteria. However, hypothesis II, that the "best" angle determined from each of the above criteria is the same, was rejected. This can be verified from Table 13. The rate of performance was highest at 30°, while 0° required the least force-time and 150° had the maximum accuracy.

It was decided to study the pattern of change in performance from the three criteria due to weight in the same units. This was accomplished by computing percent increase over the light stylus and the results are shown in Table 14. Time per movement instead of rate of performance was used, since time is inversely proportional to the latter. These results are also graphically shown in Figure 18. The rate of increase in accuracy with increase in weight was very slow and the curve started declining

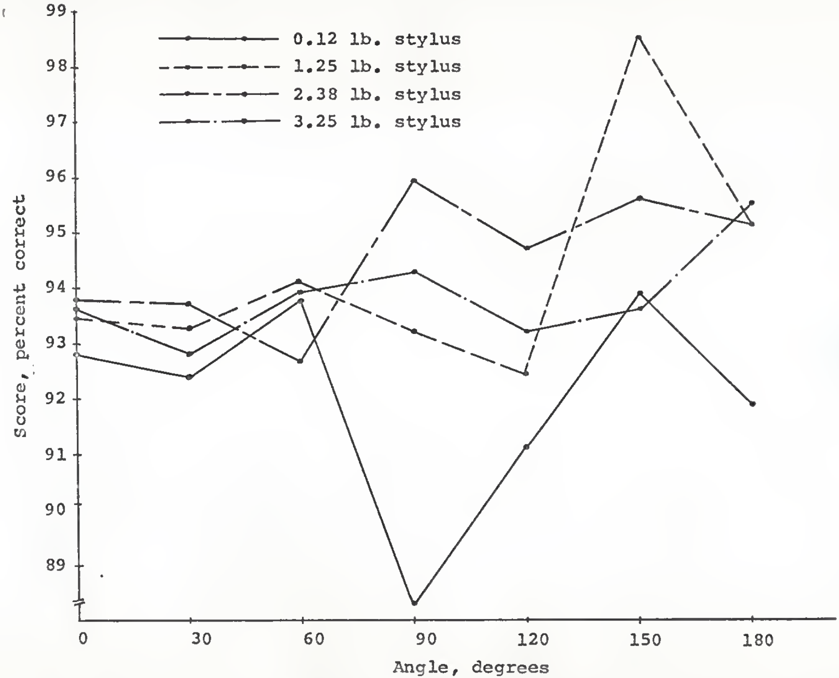


Figure 16. Effect of angle on percent accuracy at each of the four weights

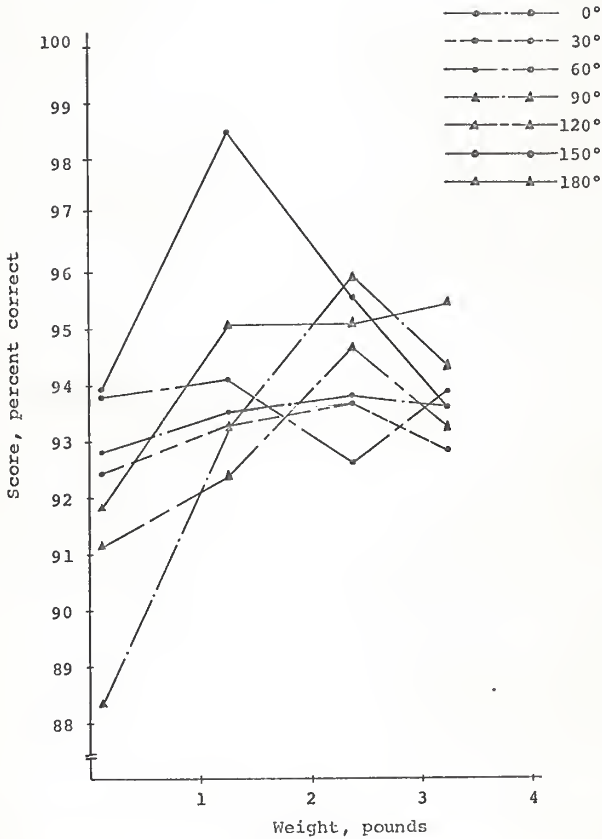


Figure 17. Effect of weight on percent accuracy at each of the seven angles.

Table 12

Mean index of performance, force-time per movement, and percent correct response score at each combination of stylus and angle

Criterion	Stylus, lbs	Angle, degrees						
		0	30	60	90	120	150	180
Index of performance, bits/sec	0.12	12.35	12.91	12.58	12.42	11.77	11.07	10.65
	1.25	11.35	11.82	11.51	11.25	11.12	10.52	10.18
	2.38	10.52	11.17	10.83	10.36	10.31	10.05	9.50
	3.25	10.05	10.54	10.39	10.21	9.95	9.66	9.19
Force-time per movement, lb-secs	0.12	1.08	1.40	1.68	1.96	2.36	2.44	2.28
	1.25	1.35	1.47	1.76	2.23	2.53	2.52	2.36
	2.38	1.78	1.77	2.30	2.54	2.88	2.92	2.83
	3.25	2.35	2.33	2.73	2.87	3.33	3.30	3.35
Percent correct response score	0.12	92.8	92.4	93.8	88.3	91.1	94.0	91.8
	1.25	93.5	93.3	94.1	93.2	92.4	98.5	95.1
	2.38	93.8	93.7	92.6	95.6	94.7	95.6	95.1
	3.25	93.6	92.8	93.9	94.3	93.2	93.6	95.5

Table 13

Comparison of "Best Angles" determined from each of the three criteria

Criterion	Rank	1	2	3	4	5	6	7
		Angle, degrees						
		30	60	0	90	120	150	180
Index of performance, bits/sec		11.61	11.33	11.07	11.06	10.79	10.33	9.88
		0	30	60	90	180	120	150
Physiological cost, lb-secs		1.64	1.74	2.19	2.40	2.71	2.77	2.79
		150	180	60	0	30	120	90
Percent correct score		95.4	94.4	93.6	93.4	93.1	92.9	92.9

Note: The performance in each case is averaged over all the styli and subjects. Those underlined by the same line are not statistically different ($\alpha < .05$)

Table 14

Percent increase in criteria over the base condition

Criterion		Stylus, lbs 0.12*	1.25	2.38	3.25
Time per movement, seconds		.418	.450	.481	.500
	% increase over base condition	-	12.4	15.0	17.2
Force-time per movement, lb-secs		1.89	2.03	2.43	2.89
	% increase over base condition	-	7.4	28.6	53.0
Percent correct response		92.0	94.3	94.5	93.9
	% increase over base condition	-	2.5	2.7	2.1

* Base condition

Note: The performances are averaged over all angles and subjects.

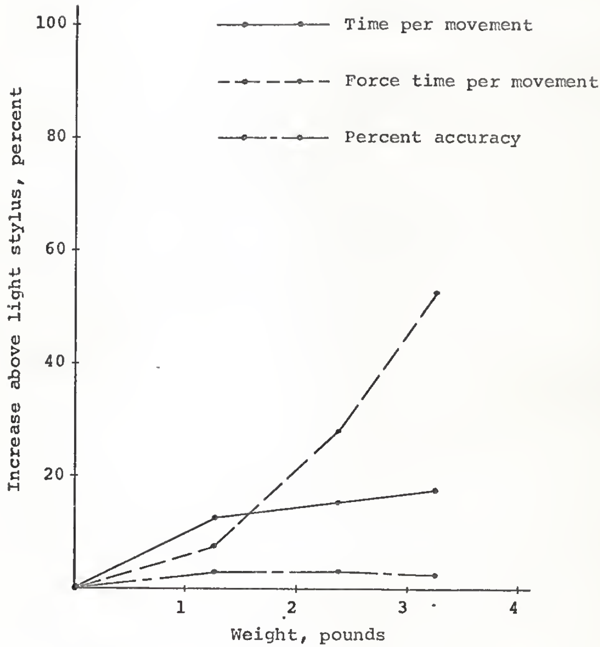


Figure 18. Relationship of weight and percent increase in criteria above the base condition of 0.12 pound stylus

at heavier weights. The time increased very sharply for the second (1.25 pound stylus) and it then followed a linear trend. The physiological cost, on the other hand, increased at a considerably faster rate with the increase in weight. This indicates that the three criteria for measurement of work, time, physiological cost, and accuracy, do not agree.

As an interesting sidelight, the experimental time values were compared with the times calculated for the same weight and motion using MTM. The MTM time was calculated using the basic formulas shown in Table 15 (Karger and Bayha, 1958). Though the percentage disagreement was considerable for the light stylus, it decreased as the weight of the stylus increased. On the average, there was a .026 sec. per pound increase in time, or an average of 6.27% increase per pound, which is considerably more than the 1.1% per pound weight allowance for dynamic factor used by MTM.

An attempt was made to test the validity of the formulation suggested by Konz for task difficulty due to pure physical effort. The formulation is restated.

$$ID_W = \text{Log}_2 \frac{W_A + W_C}{W_A} \text{ bits} \qquad \ldots\ldots\ldots(12)$$

where ID_W = Index of difficulty due to weight alone in bits

W_A = Weight of the arm with which movement is made

W_C = Weight moved.

Because the formulation is a ratio of weights, units of weight are not specified.

Table 15

Comparison of experimental results with MTM

Weight, pounds	Experimental times, seconds	MTM times, seconds	MTM-Exp. times, seconds	% Disagreement
0.12	.418	.569	.151	36.1
1.25	.450	.576	.126	28.0
2.38	.481	.583	.102	21.2
3.25	.500	.588	.088	17.6

Sample MTM calculation for 3.25 pounds stylus

Effective Net Weight (ENW)	= 3.25 pounds
Distance moved	= 16 inches
Static TMU	= 0
Dynamic Factor	= 1.000 + 0.011 (ENW)
	= 1.036
Move time	= (15.8 TMU)(1.036)
	= 16.369 TMU
(16.369 TMU)(0.036)	= .588 seconds

Notes:

1. Experimental times are averaged over angles.
2. % disagreement was calculated using the experimental times as a base.
3. The 15.8 TMU used in calculation of the move time was the basic time for a class B move obtained from the MTM table.

Using the above formulation, the information content due to weight alone was found to be 0.29, 0.50, and 0.67 bit for 1.25, 2.38 and 3.25 pounds styli respectively. The weight of the arm was taken as 4% of the body (Contini, Drillis, and Bluestein, 1963). The index of task difficulty for the amplitude and tolerance conditions of the present task was 5.0 bits as calculated from Fitts' formulation and 4.07 bits from Welford's formulation. Table 16 shows the total information content of the task for the four variations of weight. When time per movement was plotted against the total task difficulty, linear relationships were obtained. Figure 19. Thus, Konz's formulation did take into account the effect due to pure physical effort, at least for the conditions of this experiment. It made no difference when Konz's formulation was used along with Fitts' formulation or Welford's formulation except that the magnitude of task difficulty was lowered in the latter case.

In order to test hypothesis III that inward motions are more accurate than outward motions, percent correct accuracy at the inner and outer targets was calculated separately and the difference, outward value subtracted from inward, was analyzed by a three-way analysis of variance. Table 17 shows the differences at each condition for each of the eight subjects and the analysis of variance of these data is shown in Table 18. The main effects of subjects and angles were found significant and those of styli and all the interactions were not significant.

Table 16

Mean time per movement and index of performance averaged over eight subjects

Stylus,lbs	t	ID	ID'	ID_W	$(ID+ID_W)$	$(ID'+ID_W)$	I_{PF}	I_{PW}	I'_{PF}	I'_{PW}
0.12	.418	5.00	4.07	0.00	5.00	4.07	11.96	9.75	11.96	9.75
1.25	.450	5.00	4.07	0.29	5.29	4.36	11.10	9.05	11.88	9.70
2.38	.481	5.00	4.07	0.50	5.50	4.57	10.39	8.45	11.43	9.52
3.25	.500	5.00	4.07	0.67	5.67	4.74	10.00	8.14	11.34	9.48

Key: t = Time in seconds for one movement from inner to outer target (averaged over all angles)

ID = Index of difficulty in bits calculated from Fitts' formulation

ID' = Index of difficulty in bits calculated from Welford's formulation

ID_W = Index of difficulty for pure physical effort in bits calculated from Konz's formulation

I_{PF} = Index of performance in bits/sec = ID/t

I_{PW} = Index of performance in bits/sec = ID'/t

I'_{PF} = Index of performance in bits/sec = $\frac{ID+ID_W}{t}$

I'_{PW} = Index of performance in bits/sec = $\frac{ID'+ID_W}{t}$

Fitts formulation $ID = \text{Log}_2 \frac{A}{.5W}$

Welford's formulation $ID' = \text{Log}_2 \frac{A+.5W}{W}$

Konz's formulation $ID_W = \text{Log}_2 \frac{W_A+W_C}{W_A}$

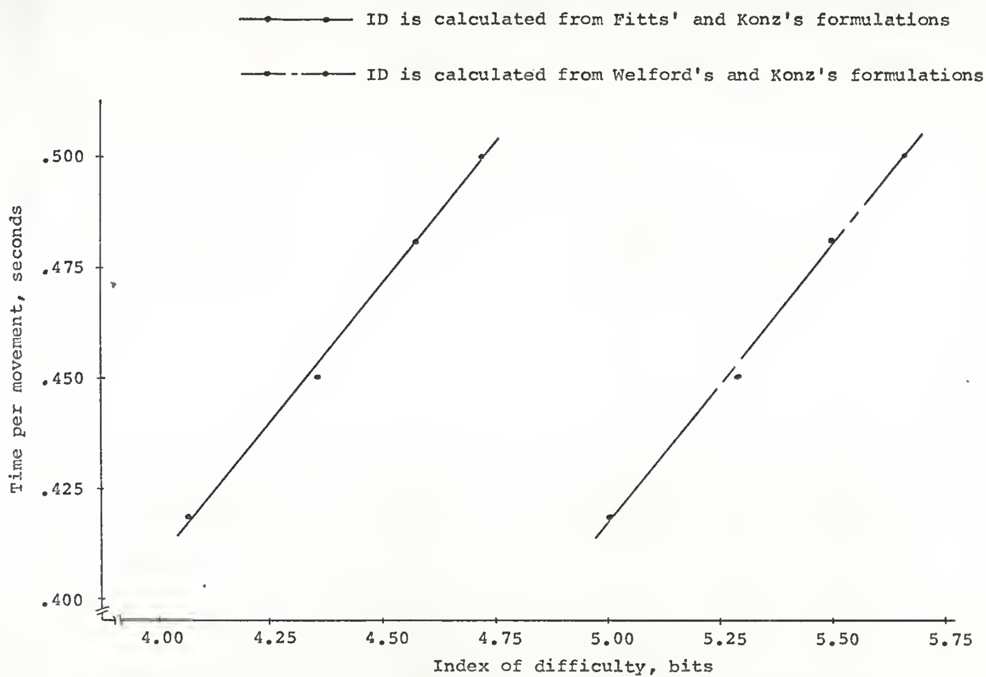


Figure 19. Relationship between information content of the task and time per movement when effect of weight is accounted for by the Konz's formulation

Table 17

Difference between the percent correct response scores of inward and outward movements at each combination of stylus and angle for each of the eight subjects

Subject	Stylus, lbs	Angle, degrees 0	30	60	90	120	150	180	Average
1	0.12	0.0	0.0	- 7.4	0.0	- 0.6	-16.0	0.0	- 3.4
2		0.0	0.0	0.0	0.0	4.2	0.0	0.0	0.6
3		11.6	2.9	- 3.1	2.9	- 0.5	-10.3	- 4.4	- 0.1
4		0.0	- 0.9	4.2	-12.1	-18.6	- 4.2	- 9.1	- 5.8
5		- 4.5	-18.7	- 7.3	-27.2	- 7.3	0.0	-18.7	-12.0
6		13.9	- 0.9	- 2.9	6.5	- 8.5	-13.4	- 3.1	- 1.2
7		2.7	- 7.3	- 4.2	1.6	- 0.6	7.7	- 5.5	- 0.8
8		- 7.5	- 5.4	- 5.2	3.4	- 6.7	- 8.8	9.5	- 2.9
Average		2.0	- 3.8	- 3.2	- 3.1	- 4.8	- 5.6	- 3.9	
1	1.25	0.0	- 0.3	0.0	- 0.7	- 3.8	0.0	0.0	- 0.6
2		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3		6.7	2.6	6.7	0.0	- 3.7	0.0	0.0	1.8
4		2.5	3.5	- 5.5	-18.2	- 1.6	0.0	5.0	- 2.0
5		- 0.4	6.2	7.8	-11.3	-11.7	- 4.2	- 4.2	- 2.6
6		- 1.2	- 9.8	- 6.7	5.1	3.1	3.4	- 4.5	- 1.5
7		0.0	9.0	-12.9	6.4	- 4.5	4.2	- 0.3	0.3
8		- 5.7	- 2.8	2.9	- 6.3	- 0.5	- 3.3	0.0	- 2.2
Average		0.2	1.1	- 1.0	- 3.1	- 2.9	0.0	- 0.5	
1	2.38	- 4.5	4.2	- 4.2	- 4.5	0.0	0.0	0.0	- 2.1
2		0.0	4.2	5.0	5.0	0.0	0.0	0.0	2.0
3		- 7.2	- 0.6	3.6	0.0	- 8.4	- 3.8	0.0	- 2.3
4		- 4.5	- 5.0	- 9.1	- 0.3	- 4.1	-15.0	10.0	- 4.0
5		- 6.8	-18.9	-19.5	- 4.8	- 0.4	-26.9	- 0.7	-11.2
6		- 2.5	- 6.1	- 0.8	- 9.3	- 4.8	- 0.4	-11.5	- 5.1
7		- 0.6	0.0	-13.8	- 0.3	- 3.2	0.0	5.6	-17.6
8		- 0.5	- 5.5	- 0.2	0.0	-10.5	0.0	- 0.5	- 2.3
Average		- 3.2	- 3.5	- 4.9	- 1.8	- 3.9	- 5.8	0.6	
1	3.25	- 4.5	- 9.5	9.1	- 0.3	- 4.5	0.0	0.0	- 0.1
2		0.0	- 5.0	0.0	- 5.6	0.0	0.0	0.0	- 1.5
3		- 3.8	0.0	- 3.6	2.7	3.8	- 4.2	4.2	- 0.1
4		4.5	-14.1	0.4	0.0	- 9.1	- 6.2	-10.0	- 4.9
5		- 4.8	10.0	- 8.2	-18.1	-33.2	3.2	-13.2	- 9.2
6		- 3.7	- 9.0	- 2.3	2.6	9.4	- 3.5	8.1	0.2
7		4.5	5.0	0.0	-10.0	- 4.6	4.5	4.5	0.6
8		- 3.3	- 3.3	-10.3	- 3.3	0.0	- 3.8	- 7.6	- 4.6
Average		- 0.3	- 3.2	- 1.9	- 4.0	- 4.8	- 1.2	- 1.8	
Grand Average		- 0.3	- 2.4	- 2.7	- 3.0	- 4.1	- 3.2	- 1.5	

Table 18

Analysis of variance of difference between inward and outward percent correct response score

Source	df	MS	F
Subjects	7	.049	6.21**
Styli	3	.014	2.70
Angles	6	.010	3.59**
S x St	21	.005	0.65
S x A	42	.006	0.76
St x A	18	.005	0.52
S x St x A	126	.009	1.20
Residual	224	.008	
Total	447	-	-

** $p < .01$

Mean differences, averaged over angles, for each of the four styli are shown in Table 19. Weight did not have any significant effect on the accuracy of inward and outward motions, although outward motions were more accurate than inward, since all the means are negative.

Table 20 gives the mean value at each angle and the comparison among these means with a Duncan's New Multiple Range Test ($\alpha < .05$). The only conclusion that can be drawn is that there was significant difference between 120° and 0°. Since all the means were negative it can be concluded that outward motions were more accurate than inward. The accuracy of moving outward, which is maximum around 120° to 150°, declined as the angle was shifted either clockwise or counter-clockwise. This effect is independent of styli since neither styli or styli x angles interaction was significant. On the basis of these results, hypothesis III was rejected. On the average outward motions were 2.5% more accurate than inward motions.

An attempt was made to find out whether there was any correlation among the three criterion measures. Spearmans correlation coefficients betwcen the mean values of

a) rate of performance and force-time,

b) rate of performance and percent accuracy,

and c) force-time and percent accuracy,

were, respectively, -0.35, -0.36, and -0.67 and these were non-significant.

Table 19

Mean difference between inward and outward percent correct response score at various conditions

1. Averaged over angles

Stylus, lbs.	0.12	1.25	2.38	3.25
Difference*	-3.2	-0.9	-3.2	-2.5

2. At each combination of angle and stylus

	Angle, degrees						
Stylus, lbs.	0	30	60	90	120	150	180
0.12	2.0	-3.8	-3.2	-3.1	-4.8	-5.6	-3.9
1.25	0.2	1.1	-1.0	-3.1	-2.9	0.0	-0.5
2.38	-3.2	-3.5	-4.9	-1.8	-3.9	-5.8	0.6
3.25	0.3	-3.2	-1.9	-4.0	-4.8	-1.2	-1.8

*Not statistically different from each other

Table 20

Results of DNMR Test as applied to mean difference between inward and outward percent correct response score averaged over styli

Rank	1	2	3	4	5	6	7
Angle, degrees	120	150	90	60	30	180	0
Difference (in-out)	-4.1	-3.2	-3.0	-2.7	-2.4	-1.5	-0.3

Note: Differences underlined by the same line are not significantly different ($\alpha < .05$).

DISCUSSION

The significant effect of weight on time and physiological cost is in agreement with Barta (1962), who also found that force-time increased at a considerably faster rate than time with increase in weight in a two-handed movement. However, an increase in accuracy with increase in weight was rather unexpected, although similar results were obtained in the pilot study which compared the performance with only two styli. One explanation could be that there is more proprioceptive feedback due to the contractions of antogonistic muscles when the arm is making movements involving weights.

The effects due to weight and direction were found to be independent of each other. As far as the direction of movement was concerned, the results of this experiment for two criterion measures, speed and physiological cost, are in agreement with those obtained by other investigators (Briggs, 1955; Schmidtke and Stier, 1961; Wu, 1965; Konz, 1967b; Rathore, 1968). For the right-handed moves, movements to the right were more efficient than movements to the left. Thus, it seems that the same conclusions are applicable for movements involving weights. The only surprising result was that maximum accuracy was found at 150 degrees. Two reasons can be given. First, the subjects were asked to emphasize speed as well as accuracy. Secondly, percent correct accuracy instead of correct response score was used to eliminate the variability due to high scores at certain angles.

Briggs and Rathore, who used the criterion which was a combination of speed and accuracy, analyzed the correct response score and no statistical analyses were carried out on the error data. For the right hand movements, Rathore found that the lowest error score, 0.68%, was at 120 and 150 degrees and the highest error score, 1.28%, was at 30 degrees and these results are in agreement with those of this experiment. The responses were fairly accurate at all the angles in the present experiment and the difference between the highest and lowest accuracy was very small, 2.4%.

It is very difficult to explain the negative correlation among the three criterion measures. However, the result, that movements from center to right were 12.0% faster and required 39.5% less force-time than movements from center to left, partially justifies the negative correlation coefficients.

More accuracy at the outward than inward motions is in agreement with the results of Briggs. Also the result that advantage of outward motions, which was maximum around 120 degrees started declining as the angle was shifted either clockwise or counterclockwise, is in line with Wu, although his criterion was force-time. It is, however, felt that these results might have been affected and misleading, as the criterion was the difference between the percent correct response scores rather than correct response scores.

The weight of the stylus did not have any significant effect on the accuracy of in and out motions. This is in agreement with

the results of MTM Research Association (Rapheal, 1955) who found that the weight did not have any real indicated difference in performance times of in and out movements.

One important feature of the present experiment should be noted: the accuracy at the inward and outward motions was studied successively in the same task. All the other investigators except Wu studied the behavior of in and out motions separately. It is very unlikely to find an assembly operation similar to the task of this experiment. It will be a good idea to study the effect of weight on the speed or accuracy of in and out motions, independently.

One very important outcome of this experiment was the development of a formulation of task difficulty for pure physical effort in information theory terms. The rate of performance for the four styli varied from 12.0 to 10.0 bits/sec. - a variation of about 17%. But when the task difficulty due to the weight was also taken into account the rate varied from 12.0 to 11.3 bits/second - a variation of about 5%, and a linear relationship was obtained between the time to perform the task and the information content. These results confirm the findings of Fitts who found that the performance capacity of the human motor system plus its associated visual and proprioceptive feedback mechanisms, is relatively constant over a wide range of amplitudes and tolerances.

The rational basis for the Konz's formulation can be explained in a manner similar to one suggested by Fitts. The difficulty index, according to Fitts, specifies the minimum information re-

quired on the average for controlling or organizing each movement. Now, the number of sets of muscles required for each movement increases as the weight carried increases. Thus the minimum organization required of a particular movement is defined by the specification of one from among several possible sets of muscles, which control the movement.

One interesting feature of this formulation is that the index will never be negative since it becomes zero when weight carried is zero.

The tolerance and amplitude conditions were kept constant in the present experiment. Future experimentation should be done in this area to test the validity of the above formulation for a wide variety of amplitudes and tolerances.

SUMMARY AND CONCLUSIONS

The effect of weight and direction on the speed, accuracy and the physiological cost of right hand movements was investigated. The task consisted of tapping two identical targets a fixed distance apart, alternately, with a metal-tipped stylus. Three criterion measures were used:

a) Rate of performance in bits/second as calculated from information theory

b) Physiological cost in pound-seconds as measured with a force platform

c) Percent correct response

The direction of the movement was varied from 0 to 180 degrees in increments of 30 degrees while the weight of the stylus was varied through four steps (.12, 1.25, 2.38, and 3.25 pounds). Eight right-handed graduate students served as subjects.

The data were analyzed by analysis of variance and the means were tested by Duncan's New Multiple Range Test. For the task conditions of this experiment, it was concluded:

1. The rate of performance, physiological cost, and percent accuracy were significantly affected by weight and direction.

2. With increase in weight, consistent increments were observed in physiological cost per movement and percent accuracy while the rate of performance decreased consistently.

3. The rate of performance was highest at 30 degrees while 0 degrees required the lowest physiological cost and 150° had the maximum accuracy.
4. The effects of weight and direction were independent of each other for all the three criterion measures.
5. The three criteria were not significantly correlated with each other. However, with increase in weight, percent accuracy increased at a rate of 0.01% per pound, time per movement increased at a rate of 6.27% per pound, and physiological cost/movement at a rate of 17% per pound.
6. Outward motions were signficantly more accurate than inward motions and this was unaffected by weight.
7. Direction did have a significant effect on the accuracy of in and out motions. The accuracy of outward motions, which was maximum at 120 degrees, declined as the angle was shifted either clockwise or counter-clockwise.
8. A formulation for task difficulty due to pure physical effort was suggested in information theory terms. When the information content due to weight was taken into account, the rate of performance was fairly constant over the range of weights considered in this experiment.

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A STUDY OF EFFECT OF WEIGHT AND DIRECTION ON THE SPEED, ACCURACY, AND PHYSIOLOGICAL COST OF ONE HAND MOTIONS IN THE HORIZONTAL PLANE

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ABSTRACT

The effect of weight and direction on the performance of right hand movements of eight right-handed subjects was investigated in a reciprocating tapping task using three different criterion measures, rate of performance as measured from information theory concepts, physiological cost as measured by a force platform, and the percent correct response score. Seven variations of angle (0, 30, 60, 90, 120, 150, and 180 degrees) and four variations of weight (.12, 1.25, 2.38, and 3.25 pounds) were studied.

It was concluded:

1. The rate of performance, physiological cost, and percent accuracy were significantly affected by weight and direction.
2. With increase in weight, the accuracy increased at a very low rate, while time per movement increased at a little higher rate and physiological cost per movement increased at a greater rate.
3. The "best" angle from each of the above three criteria was not the same.
4. The effects due to weight and direction were independent of each other for all the three criterion measures.
5. Outward motions were significantly better than inward motions. Direction had a significant effect while weight did not affect the accuracy of in and out motions.
6. A formulation for task difficulty due to pure physical effort was suggested in information theory terms. The formulation was valid for the data of this experiment.